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Interrelationships Among Circumstellar, Interstellar, and Interplanetary Dust

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Interrelationships Among Circumstellar, Interstellar, and Interplanetary Dust

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PREFACE

As humans, the tools we have developed for exploration of the universe include observation and inference. We use these tools to their limits in exploration of the major questions of our intellectual life: the origin and fate of the universe. We observe matter that is either "bright" or "dark" in terms of its photon output. Optically bright matter tends to be in a hot, gaseous phase in the universe, while dark matter is seen in silhouette against background light. Dark matter in interstellar space tends to be cold, solid phase material, and is seen in abundance at infrared wavelengths. In either case, the matter in these phases exists as a result of its history. Retracing this history and projecting its future is the focus of the efforts directed at the study of cosmic material. This workshop represents part of that effort.

Stars have been identified as the point of origin of much of the dust grain material observed in cosmic environments. The interstellar medium has been identified as the transporter and processor of grains. The interplanetary medium is the depository for these grains, and when they fall to earth in meteorites, we then can examine first-hand the tangible evidence of cosmic history locked in a solid body.

Participants in this workshop grappled with several questions: Is there evidence that material is being transported from stars ultimately to the laboratory? Possibly. Supernova and s-process isotopic enrichments produced only in stars have been found in meteorites. However, our theoreticians are embarassingly clever at destroying dust grains in interstellar shock fronts much more rapidly than replacing them with new grains. Despite this intellectual conundrum, abundant interstellar grains are evident, so the stellar material must be at least partially preserved. Finally, the best match, at present, to certain previously unidentified interstellar dust spectral features is an organic material, the polycyclic aromatic hydrocarbons (PAHs).

This report contains the labors of a highly interdisciplinary mix of fifty astronomers, planetary scientists, chemists and experimentalists who shared information and confronted issues in frontier areas at the largely undefined interfaces of their respective specialities. The invited talks, contributed papers, discussions and working group reports highlight the state of knowledge of this field in an unique way. We invite you to share the excitement felt at the Workshop.

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Introduction

The Workshop on the Interrelationships among Circumstellar, Interstellar, and Interplanetary Grains was held at the Aspen Institute's Wye Plantation Conference Center in Maryland, February 27-March 1, 1985. All members of the Science Organizing Committee (SOC) felt that a "face-to-face" meeting between astronomers, astrophysicists, planetary scientists, and meteoriticists was long overdue. The importance the organizing committee and invited participants attached to the proposed interdisciplinary nature of the agenda is reflected by the rapidity with which such a productive meeting could be organized. The first teleconference of the SOC took place on September 6, 1984, less than six months prior to the workshop. The purpose of the workshop was to focus attention on the interdisciplinary nature of "cosmic dust" research and to make astronomers and planetary scientists more aware of the developments that had occurred outside of their own research areas over the last decade or so. A secondary objective was to stimulate cross-disciplinary research between workers whose expertise was potentially complementary, but who had not previously been aware of the scientific justification for such collaborative efforts.

The first day was devoted to the presentation (and discussion) of seven invited review papers. The talks covered circumstellar, interstellar, and interplanetary materials; both observational and theoretical aspects were presented. Speakers were not only asked to "give the facts," but also to discuss uncertainties and model dependent conclusions in a candid manner. Although illness prevented the presentation of a talk covering laboratory aspects of grain research, that paper is included in this volume for completeness. The evening of day one was devoted to a poster session and marked by an extraordinary amount of cross-disciplinary discussion. Abstracts of these poster presentations are included in this volume.

On day two, a series of working group meetings were held. The morning sessions were devoted to three parallel working groups which were asked to summarize the "facts" and relevant questions in the fields of circumstellar, interstellar, and interplanetary dust. The afternoon was reserved for discussion of the relationship between circumstellar and interstellar grains, and between interstellar and solar system materials in two simultaneous meetings. First drafts of all working group reports were written during and immediately after the group meetings. Summaries of working group results were presented in plenary session so that all participants had the opportunity to comment on the anticipated content of the reports. The purpose of the reports was to focus the thoughts of the participants on interdisciplinary approaches that might be applied to grain research. A secondary aspect of these reports was their utility as a "quick reference primer" for use by interested researchers working outside of the field covered by the report.

We note here that the methods of the five working group chairmen varied considerably. All worked diligently to produce reports reflecting the consensus of their groups; however, the style of each report was determined by the individual group chairmen. Each report was sent to all participants for comment, rewritten by the group chairman, and edited at NASA Headquarters.

On the morning of day three, we held a roundtable discussion in which each participant was asked to state the "one burning question" he or she would like to see answered or at least addressed in the near future. The edited transcript of this session is included here because it makes thought-provoking reading. It also constitutes a source of interesting thesis and dissertation topics.

In this same vein some personal opinions of the participants are contained in the "issue response forms" received before, during, and after the meeting. These "Issues" and response forms were initially intended to stimulate interdisciplinary thinking by the participants, and to serve as an aid to group chairmen in writing their reports. The response forms also served to insure that unorthodox ideas and alternative hypotheses of participants were included in the proceedings of the workshop, even when such ideas did not easily fit within the structure of a working group report.

All participants seemed to feel that the workshop was well worth their efforts. A considerable amount of interdisciplinary exchange occurred informally among participants and it remains to be seen whether or not new research that crosses traditional discipline boundaries has been stimulated. If this happens the workshop can be considered a complete success.

OBSERVATIONAL CONSTRAINTS ON CIRCUMSTELLAR DUST

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I. INTRODUCTION

There is an enormous range in the properties of stars are are losing mass. In this review I concentrate on those red giants that are responsible for injecting roughly half or more of the material into the interstellar medium.

During the past 15 years, there has been a dramatic improvement in our understanding of mass loss from red giants. The stars that are losing the most mass are enshrouded by cold envelopes of dust and gas so they are primarily infrared and radio sources; consequently, with the development of appropriate instrumentation, it has been possible to reach a much deeper understanding of the mass loss from these stars. Optically, stars such as IRC +10216, the carbon rich mass losing prototype, are extremely faint, yet at 10 μm, many of the brightest objects in the sky are highly evolved red giants (Kleinmann, Gillett and Joyce 1980).

In this review, I concentrate on describing the physical properties of the outflows. Earlier work has been reviewed by Zuckerman (1980), I focus on the results obtained during the past 5 years. Also I do not, for example, discuss either the importance of the grains in driving the outflows by radiation pressure or models for how the grains might form. In Section II, I describe the physical properties of the gaseous outflows while in Section III, broad-band observational constraints on the dust are described. In Section IV, spectroscopic studies of the grains are reviewed.

II. PHYSICAL PROPERTIES OF THE GAS OUTFLOWS

In almost all the stars of interest, most of the outflowing gas is hydrogen, and the first task is to describe the physical state of this gas. Searches for atomic hydrogen at 21 cm from the outflows from red giants have generally been unsuccessful (Zuckerman, Terzian and Silverglate 1980; Knapp and Bowers 1983). In two special circumstances, α Sco and NML Cyg, some of the circumstellar hydrogen is ionized, and it has been possible to detect the total mass outflow from measurements of the radio free-free emission (Hjellming and Newell 1983; Morris and Jura 1983). However, in most stars, it seems that the bulk of the outflowing gas is H_2. While in a few circumstances the H_2 is excited by shocks (Beckwith, Persson and Gatley 1978); current technology does not enable us to study the bulk of the molecular hydrogen. Therefore, most of the spectral diagnostics of the outflowing material have been performed by studying the minor constituents such as CO, OH and H_2O.

Because it is so stable, standard condensation theories predict that the first molecule to form as the gas cools is CO (Salpeter 1977), and the CO consumes all the available oxygen or carbon. That is, a star is carbon rich and has free carbon only if $[C]/[O] > 1$; otherwise the star is oxygen-rich. The expectation that CO is abundant in the outflows from late-type giants is well supported by observations, and a convenient way to study the circumstellar CO has been its radio emission. Recent surveys have increased to roughly about 100 the number of stars from which CO has been detected in the radio (Knapp and Morris 1985; Zuckerman and Dyck 1985).

From observations of the radio CO profile, it is directly possible to measure the outflow velocity from the full width at zero intensity of the line

(for example, Morris 1975). The characteristic outflow speed is 15 km s^{-1}; outflow velocities range from 4 km s^{-1} to greater than 40 km s^{-1}. The outflow velocity is correlated with the period of pulsation of the red giant (Morris et al. 1979) suggesting that pulsations may be related to the rate of mass loss (see also DeGioia-Eastwood et al. 1981). Also, at least in oxygen-rich stars, with considerable scatter, it appears that v varies as $L^{1/4}$ (Jura 1984b).

With relatively few assumptions, it it also possible to derive the mass loss rate, M, from the radio CO observations. The CO radio lines are excited by collisions with ambient H_2 and by flourescence that results from absorption in infrared vibrational transitions. From the shapes of the radio line profiles, the relative intensities of the J = 2-1 and J = 1-0 rotational transitions and, in some cases, maps of the CO emission, it is possible to derive mass loss rates (Kwan and Hill 1977; Morris 1980; Jura 1983b, Knapp and Morris 1985). The major uncertainties in the analysis are the abundance of CO relative to H_2 and the distance to the star.

In the usual evolutionary scenario, these mass-losing red giants evolve into planetary nebulae (Zuckerman et al. 1977; 1978). Since observations of planetaries do not show large variations in the total amount of CNO ejected into the interstellar medium (Zuckerman and Aller 1985), the uncertainties introduced by assuming a CO abundance in the outflow are probably not dramatic. Also, while the total mass loss rate of an individual star is sensitive to the assumed distance, some relative quantities such as the dust to gas ratio in the outflow are not.

Mass loss rates from red giants cover a very wide range. The highest known values are about 10^{-4} $M_{\odot}$ yr^{-1} while there are positive detections of

loss rates as low as 10^{-8} $M_\odot$ yr^{-1}. This upper limit is probably significant since the large majority of these red giants are asymptotic giant branch stars approaches the maximum theoretical luminosity of 6 10^4 $L_\odot$ (Iben and Renzini 1983). If radiation pressure on the grains drives the matter to infinity, then $\dot{M}v \leq L/c$ and with v = 15 km s^{-1}, this implies that $\dot{M} \leq 10^{-4}$ $M_\odot$ yr^{-1}. Although a few years ago it was suggested that for carbon-rich stars, $\dot{M}v$ could be considerably larger than L/c (Knapp et al. 1982), this no longer seems to be the case (Jura 1983, Knapp 1985).

A number of important results appear in the recent survey of mass loss by Knapp and Morris (1985). Some important though still tentative findings are:

1. The mass injected into the interstellar medium by carbon-rich and oxygen-rich stars appears to be roughly comparable. (This result is in striking contrast to the optical observations that there are many more oxygen-rich stars than carbon-rich stars, a discrepancy first noted by Zuckerman et al. 1977).
2. A wide range of stars contributes to the mass ejected into the interstellar medium. As a first approximation, the amount of mass contributed by stars with mass loss rates of 10^{-4} yr^{-1} is comparable to the amount contributed by the many more stars losing 10^{-7} $M_\odot$ yr^{-1}.
3. At least 0.3 $M_\odot$ yr^{-1} are returned to the interstellar medium to the entire Galaxy by mass loss from red giants. This is at least comparable to and probably larger than all the other sources of new interstellar matter. However, because their sample of stars was not chosen on some systematic basis, definitive conclusions will not be reached until the recent comprehensive survey by Zuckerman and Dyck (1985) is completed.

Other molecules besides CO have also been used to study circumstellar shells. In oxygen-rich stars, OH, H_2O, SiO (see Zuckerman 1980) and most recently H_2S (Ukita and Morris 1983) have been found while in carbon-rich stars, a number of molecules have been found (Lafont, Lucas and Omont 1982) including, most recently, SiC_2 (Thaddeus, Cummins and Linke 1984). As described below, there is also recent evidence that large polycyclic aromatic hydrocarbons may be present in large numbers.

Isotope ratios in the mass outflows from stars can be measured in the optical, infrared and radio spectra; however, at all wavelengths there is often some ambiguity in interpreting the data. By far the most commonly studied isotope ratio is $^{12}C/^{13}C$. For α Ori, an oxygen-rich supergiant, it appears well established from infrared observations that $^{12}C/^{13}C = 6$ (Bernat et al. 1979). In the well studied carbon star, IRC +10216, the recent infrared data (Keady, Hall and Ridgway 1985) give $^{12}C/^{13}C = 35$ in reasonably good agreement with most of the older studies (Zuckerman 1980). This difference in the $^{12}C/^{13}C$ isotope ratio between these two particular stars may be characteristic of oxygen-rich and carbon-rich stars that are losing large amounts of mass. That is, Knapp and Chang (1985) find from radio measurements that $^{12}CO/^{13}CO$ is generally larger in carbon-rich stars compared to oxygen-rich stars. Also, optical studies of oxygen-rich red giants indicate $^{12}C/^{13}C$ ratios around 10 (Hinkle, Lambert and Snell 1976) which is much lower than the interstellar value of 43 ± 5 (Hawkins, Jura and Meyer 1984) and therefore cannot be characteristic of the bulk of the matter which is injected into the interstellar medium. Since carbon-rich stars contribute much of the new mass of the interstellar medium, this indirectly suggests that carbon-rich

stars have $^{12}C/^{13}C$ ratios high compared to 10. Unfortunately, classical optical spectroscopy of carbon-rich stars has not lead to precise measurements of isotope ratios. As discussed by Dominy et al. (1978) and Johnson, O'Brien and Climenhaga (1982), the inferred range for $^{12}C/^{13}C$ in the well studied carbon star V 460 Cyg is between 7.9 and 100, although the best current value is around 30.

III. BROAD BAND OBSERVATIONS OF THE GRAINS

One of the most striking results of observations of mass outflows from late-type giants is that there is a strong correlation between the gas loss rate and the amount of grains measured by their infrared emission (Zuckerman and Dyck 1985). From the observed infrared emission, it is possible to infer the dust loss rate, and this value can be compared to the gas loss rate derived from radio CO measurements described above. It has been found that while there may be fluctuations, gas to dust ratios by mass of about 100 seem to obtain (Knapp 1985, Sopka et al. 1985). In other words, for solar abundances, most of the refractory material that conceivably could be condensed onto solids actually does so. Indirect observational evidence of the gas also supports this conclusion. For example, only about 1% of the silicon is contained within gas phase SiO even though this is thought to be the major form of this element in the gas. This result is consistent with the view that most of the silicon is contained within grains (Morris et al. 1979; Jura and Morris 1985).

It seems well established that not only do the grains contain a large fraction of the material other than volatiles such as hydrogen and helium, it seems that the circumstellar grains also have sizes not too dissimilar from interstellar grains. That is, with some considerable uncertainty, there is

evidence that many of the grains have sizes within an order of magnitude of 0.1 μm. The evidence is the following:

1. Optical observations of quantities such as the intensity of Hα/Hβ emission lines in carbon stars indicate considerable circumstellar reddening (Cohen 1979). Also, molecules such as H_2O and HCN are photodissociated by ambient interstellar ultraviolet photons as they flow out of the star (Goldreich and Scoville 1976, Huggins and Glassgold 1982, Jura 1983a). Interpretation of the spatial distribution of these molecules indicates that the extinction probably continues to rise in the ultraviolet. Therefore, most of the particles in circumstellar outflows are probably not larger than 0.1 μm; otherwise the extinction would not be a strong function of wavelength.

2. Polarization of the optical (Shawl 1974) and near infrared radiation (Dyck et al. 1971) can be interpreted in terms of grains of roughly 0.1 μm size (Daniel 1982). That is, not all the grains are very small; otherwise there would be no effective scattering.

3. In the outer circumstellar envelope ($r > 10^{15}$ cm), the gas is heated by the grains streaming supersonically through the gas (Goldreich and Scoville 1976). This heating rate is sensitive to the grain size, and at least in the case of IRC +10216, the best studied circumstellar envelope around a carbon star, it appears that the mean size of a grain is 0.04 μm (Kwan and Hill 1977).

4. Papoular and Pegourie (1983) have suggested that the shape of the 10 μm feature in oxygen-rich stars requires some grains with sizes comparable to 1 μm. While it is important to understand the nature of the profile variations among different sources, this could be a result of temperature or compositional differences rather than grains having different sizes.

The overall infrared energy distribution of the light from circumstellar dust shells seems to be well understood (Rowan Robinson and Harris 1983a,b; Sopka et al. 1985). Models of the observations are most consistent with a grain emissivity that is modelled by a power law which varies more like $\lambda^{-1.2}$ rather than λ^{-2} (Campbell et al. 1976, Werner et al. 1980, Sopka et al. 1985). In carbon stars, this suggests that the grains are more likely to be composed of amorphous carbon rather than graphite.

The presence of near infrared emission indicates that some of the grains are relatively warm with temperatures near 1000 K. This is an important constraint on any formation mechanism of the grains. Also, interferometry indicates that the grains are formed within 10^{15} cm of the stars (Sutton et al. 1977, 1978, 1979, Dyck et al. 1985). This result also suggests that the temperature of formation is near 1000 K.

A very indirect argument on the location of the grain formation comes from the observed outflow velocities. If the gas to dust ratio is 100, we expect that once the grains form, radiation pressure overpowers the gravitational force exerted by the star and drives the material to infinity. If the grains form close to the star, then the outflow velocity is predicted to be larger than the characteristic speed of 15 km s^{-1}. On the other hand, the result that v varies as $L^{1/4}$ is consistent with condensation of a large amount of material at 1000 K (Gehrz and Woolf 1971, Jura 1984a) or roughly 10^{15} cm from the star of luminoisity 10^4 L_O.

A final point is that the line profiles in circumstellar outflows may provide valuable information on the condensation sequence. In the spectrum of

IRC+10216, Keady, Hall and Ridgway (1985) have measured broad troughs in the P Cygni lines. A possible model to explain the observations is that as the grains cool in the outflow, they can accumulate molecules that were too volatile to condense onto the solid at the higher temperature characteristic of the grains closer to the stars. Rapid accumulation of mantles might occur at preferred temperatures and this would result in impulsive acceleration of the material as the grain opacity becomes larger (Jura 1984b). Therefore, it may be possible with sufficiently good data to indirectly infer the condensation sequence in the outflow from a star.

IV. SPECTROSCOPY OF CIRCUMSTELLAR DUST

Although the broad band measurements can provide useful constraints on the nature of the dust, they do not provide nearly as much information on the detailed structure of the grains. Merrill (1979) and Kleinmann, Gillett and Joyce (1981) have reviewed the observations of the spectra of red giants. A major result is that the oxygen rich stars display the silicate features at 9.7 μm and 18 μm while the carbon-rich stars show SiC at 11 μm. Since 1980, there have been a number of recent advances of our understanding of the grains:

1. Forrest, Houck and McCarthy (1981) have discovered a feature near 30 μm in the spectrum of carbon-rich stars. The nature of the carrier remains unidentified.

2. Draine (1984) has predicted the presence of a feature at 11.52 μm in the spectra of carbon-rich stars if the grains are composed of graphite. The absence of this feature in the spectrum of IRC +10216 is consistent with the view that the material is more likely to be amorphous carbon than graphite.

3. A few oxygen rich stars show absorption at 3.1 μm characteristic of ice (see, for example, Soifer et al. 1981). Jura and Morris (1985) have argued that gas-phase H_2O condenses onto grains once the dust temperature falls below 110 K at a sufficiently large distance from the star. Quantitatively, this model explains the presence of both gas-phase and solid-phase H_2O around OH 231.8+4.2, the star with the strongest known ice band.

4. A remarkable advance in our understanding of the spectra of the solid state material comes from the study of "unidentified" infrared emission bands between 3.3 μm and 11.3 μm. That is, in a variety of objects such as the carbon-rich planetary nebula NGC 7027, much of the radiation is carried in discrete bands rather than in a continuum (Russell, Soifer and Willner 1977). Just before NGC 7027 became a planetary nebula, it was a red giant (Zuckerman 1977, Jura 1984b) and we still can detect the outer molecular shell surrounding the inner ionized gas. The diffuse IR lines are produced at least in part in the outer molecular gas (Aitken and Roche 1983, Isaacson 1983).

The identification of the infrared features with various vibrational modes of carbon carbon bonds and carbon hydrogen bonds was suggested by Duley and Williams (1981). In an important advance, Leger and Puget (1984) described quantitatively how the observed emission features naturally result from the absorption of ultraviolet radiation by very small (~50 atom) grains; the equivalent of very large molecules. By comparing the observed spectra with laboratory studies, Leger and Puget suggested that polycyclic aromatic hydrocarbons (PAH's) are the best candidates to explain the infrared features. While there is some question as to the exact nature of these molecular carriers (Allamandola, Tielens and Barker 1985), there seems to be a good chance the basic identification of PAH's in circumstellar outflows is correct.

The proposal that the IR bands are carried by PAH's does not, by itself, describe the molecular composition. The observed bands are characteristic of specific bonds rather than specific molecules. For precise identifications, it will probably be necessary to acquire spectra of the electronic transitions.

Quite remarkably, there is some possibility that the PAH's can also explain a 50 year old problem --the origin of the diffuse interstellar bands observed optically. Leger and d'Hendecourt (1985) and van der Zwet and Allamandola (1985) have proposed that these features may be carried by PAH's that are generally present in the interstellar medium. While laboratory data do not (at least yet) support this suggestion, it may be that we do not know enough about the optical spectra of the appropriate molecules because they are ionized or are otherwise modified from normal laboratory specimens, and therefore they have not been intensively studied.

In related observations, Pritchett and Grillmair (1984) have discovered the presence of the diffuse bands 5780 Å and 5797 Å in the spectrum of NGC 7027, a carbon-rich planetary nebula that has just evolved from the red giant stage. Because much if not all of the extinction toward this object is circumstellar rather than interstellar (Jura 1984b), it is distinctly possible that the diffuse bands are carried by large carbon-rich molecules, such as the PAH's. A search for the features in oxygen rich circumstellar shells was not successful (Snow and Wallerstein 1972, Snow 1973), but further work is appropriate.

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Circumstellar Grain Formation

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1. Principal Classes of Grain-Forming Stars

It is now evident that grains are present in the outflows from many cool giant and supergiant stars. In addition to these cool evolved stars, nova explosions are also known to sometimes show evidence for dust condensation (Gehrz *et al* 1984 and references therein). Less is known about dust formation in the neighborhood of protostars, but this may play a significant role in grain reprocessing (Burke and Silk 1976). The present paper will concentrate on dust formation around cool giants and supergiants.

Cool stellar atmospheres and envelopes are quite cleanly separated into two very different classes: those in which oxygen is more abundant than carbon ($C/O < 1$), and those in which carbon is more abundant than oxygen ($C/O > 1$). In both cases, the cool atmosphere forms CO to the point of almost fully locking whichever of the two elements is least abundant; the remaining atoms of the more abundant of C or O then dominates the chemistry of the cool atmosphere.

(a) Oxygen-Rich Outflows

The first abundant condensate expected in a cooling atmosphere with cosmic abundances ($C/O \approx 0.5$) and densities $n_H \approx 10^8 \mathrm{cm}^{-3}$ would be silicate minerals such as olivine $(Mg,Fe)_2SiO_4$ and enstatite $MgSiO_3$ (see the review article by Salpeter 1977). These silicates appear at $T \approx 1000$K. Dusty outflows from oxygen-rich stars commonly show the 10μm "silicate feature" -- due to the Si-O stretching mode -- in either emission or absorption, thus confirming the condensation of silicates in these outflows. Betelgeuse (α Ori) is an example of a red supergiant star with a silicate emission feature; OH 0739-14 is an example of an oxygen-rich outflow with

so much dust that the silicate feature appears in absorption (Soifer *et al.* 1981).

(b) Carbon-Rich Outflows

In a carbon-rich atmosphere, some form of solid carbon will be the dominant condensate. Ideal monocrystalline graphite is the thermodynamically favored condensate, but kinetic factors will probably result in the formation of some polycrystalline carbon solid -- such as "turbostratic" graphite -- or "amorphous" or glassy carbon. Graphite and amorphous carbon have no strong infrared spectral features permitting unambigous identification, although crystalline graphite does have weak infrared resonances (Draine 1984). In addition to graphite, SiC (silicon carbide) can also condense (although somewhat later than graphite if in LTE). Silicon carbide has a spectral band in the 10.5–12μm region which was first identified in the spectrum of IRC+10216 (Treffers and Cohen 1974). IRC+10216 is perhaps the best example of a carbon-rich outflow, showing a nearly featureless infrared spectrum.

2. Grain Nucleation in Steady, Spherically-Symmetric Outflows

(a) Temperatures of Circumstellar Grains

The temperature of a circumstellar dust grain is essentially determined by a balance between the rate of absorption of radiation from the stellar surface and the rate of thermal infrared emission by the grain. The temperature therefore is quite strongly dependent upon the absorptive properties of the particle at the wavelengths where most of the stellar radiation is -- typically $\sim 1\mu$m for the cool stars which concern us here. Clean terrestrial silicates have relatively small absorption coefficients in this wavelength region. For a star with a temperature $T_* = 3000$K, a clean olivine grain at a radius $r \approx 1.6 R_*$ will be at the condensation temperature $T \approx 1000$K. For a star emitting as a $T = 2500$K blackbody, a clean olivine grain at $r = 1.3 R_*$ will have $T = 1000$K. Thus clean olivine particles can exist

relatively close to the surfaces of cool stars.

However, there is strong evidence that the silicate dust surrounding at least some stars must be much "dirtier" than the clean olivine discussed above. This is because the grains must be sufficiently absorptive to absorb enough of the stellar radiation to reprocess it into the observed infrared emission (Jones and Merrill 1976). For a star with T_{*}=3000K, these dirty silicate particles would have T=1000K at $r\approx4.5R_{*}$. Thus we see that the "condensation radius" depends quite sensitively on the assumed grain optical properties.

(b) Kinetic Considerations

Consider a spherically-symmetric steady outflow with mass loss rate $\dot{M}$. Suppose that a grain is injected into the outflow at radius r_1. If the sticking probability is s, and depletion of the vapor is neglected, the amount Δa by which the grain radius will increase is

$$\Delta a = 200\text{Å}\, f_{-4} s \left(\frac{R_*}{r_1}\right)\left(\frac{\dot{M}}{10^{-6}M_\odot\,\mathrm{yr}^{-1}}\right)\left(\frac{L}{10^4 L_\odot}\right)^{-1}\left(\frac{T_{eff}}{2500\mathrm{K}}\right)^{2}\left(\frac{v}{10\mathrm{km\,s^{-1}}}\right)^{-2} \qquad (1)$$

I have assumed a grain density $3\,\mathrm{g\,cm^{-3}}$, an average atomic mass 25 amu, and a mean speed of $1\,\mathrm{km\,s^{-1}}$ for the condensible gas atoms. The condensible gas atoms are assumed to have a density $n=10^{-4}f_{-4}n_H$ ($f_{-4}\approx1$ being appropriate for condensation of silicate grains from gas of cosmic abundances Si/H= 3.3×10^{-5} Mg/H = 2.6×10^{-5}, Fe/H =4.0×10^{-5}). It is clear that grain growth in such an outflow is severely limited by kinetic considerations, completely aside from the question of grain nucleation

(c) Nucleation Theory and Its Limitations

As seen above, grain *growth* is subject to severe kinetic limitations. Perhaps an even more severe limitation is that posed by the need to nucleate solid particles out of the vapor. The problem here is that small particles or clusters are not as stable as bulk material, because surface free energy makes a substantial

contribution to the overall free energy of the cluster. Thus, at a given degree of supersaturation, there is a minimum particle size (the "critical cluster size") below which clusters are more likely to evaporate than to grow. Statistical fluctuations are responsible for a finite rate of formation of clusters exceeding the critical cluster size; once having attained this size, the cluster becomes stable and will continue growing until the vapor ceases to be supersaturated.

The idealized problem of nucleation out of a *slowly* cooling vapor, always close to LTE, has been the subject of so-called "classical" nucleation theory (Draine and Salpeter 1977; Yamamoto and Hasegawa 1977). When account is taken of depletion of the vapor by cluster nucleation and growth, it turns out that specific predictions can be made of, for example, the supercooling which the vapor will undergo before the nucleation rate peaks, and the final sizes of the clusters which will form.

The theory makes a number of simplifying assumptions. One is that the "vibrational" temperature of the clusters and the kinetic temperature of the gas are the same. This condition is certainly *not* satisfied in a circumstellar flow. It is relatively easy, however, to make allowance for nonequality of the vibrational temperature and the gas kinetic temperature (Draine 1981). A second assumption is that grain growth consists of addition of monomers from the vapor, and that chemical distinctions among these monomers may be overlooked. This is certainly not correct in detail for growth of silicates, for example, as has been emphasized by Donn (1976). A third questionable assumption is that the "critical" cluster size is large enough that the free energies of these clusters may be sensibly estimated. This is a controversial issue; Draine (1979) has argued that existing information concerning the thermodynamics of small clusters suggests that their free energies *can* be meaningfully estimated, but others have disagreed (Donn and Nuth 1985). A fourth assumption is that the critical-sized clusters are large enough so that the internal degrees of freedom of the cluster are able to absorb the latent heat

released when a new chemical bond is formed at the grain surface; this latent heat can in fact lead to very small effective "sticking" coefficients for growth of small clusters (Salpeter 1973).

The applicability of "classical" nucleation theory to the nucleation of refractory materials is not clear. Donn and Nuth (1985) have argued that existing experimental studies of the nucleation of refractory materials are inconsistent with the predictions of classical nucleation theory. My own view is that "classical" nucleation theory must of course be employed with extreme caution when the critical cluster size is small, but that the theory -- for all its limitations -- is better than nothing. Obviously it would be most desirable to have a full kinetic model with state-to-state transition rates, but this is far beyond our grasp at the present time. I am also not persuaded that the experimental data really rule out the applicability of "classical" nucleation theory to refractory systems -- the experiments are extremely difficult and demanding, and I hope that more work will be done in this area. In any case, as indicated below, the chemical physics of grain nucleation -- as incompletely understood as it is -- may perhaps not be the greatest source of uncertainty in our present understanding of circumstellar grain formation.

3. Real Circumstellar Mass Flows

(a) What drives mass loss?

We observe mass loss from many cool stars, but it must be said that the mass loss mechanism remains a mystery. In extremely cool stars, grain formation itself could in principle drive the mass loss: grains could nucleate within the stellar atmosphere, and radiation pressure acting on the grains could then "lift off" the upper layers of the atmosphere. The physics of this has been discussed by Salpeter (1974a,b). Model calculations of steady mass loss from very cool

(T_{eff} =2000K) stars have been done by Deguchi (1980); Woodrow and Auman (1982) have modelled the time-dependent mass loss from cool pulsating Mira variable stars.

Convection in the envelopes of giant stars is expected to lead to substantial variations in temperature over the stellar surface. As a result, Salpeter proposed that grain formation might take place within cool patches on the stellar surface. This idea continues to have appeal, particularly for understanding mass loss from the coolest stars. However, many mass-losing stars -- such as α Ori -- are now believed to have such high effective temperatures that it is hard to believe that there could be patches cool enough for grains to form right in the stellar atmosphere, or, indeed, that grains so formed could survive as they moved away from the local cool patch and were exposed to radiation from hotter regions of the stellar surface. Remember that silicate grains cannot survive heating to temperatures significantly in excess of 1000 K.

(b) Observational Evidence for Complex Gas Flows Around Mass-Losing Stars

Accumulating observational evidence is leading to a picture where the gas flows around mass-losing stars are extremely complex. In the case of α Ori, Boesgaard (1979) has observed FeII emission lines which she interprets as originating from material at $\sim 1.8 R_*$ *falling inward* onto the star. This is hardly comforting to proponents of steady, spherically-symmetric outflow models!

Red giants with SiO masers provide another independent piece of evidence for complex outflows. Attempts to model the observed SiO maser emission from VX Sag and R Cas lead to the conclusion that the maser emission originates in clumps of gas with densities a factor of $\sim 10^2$ times greater than the density which would be appropriate to a spherically-symmetric, steady outflow (Alcock and Ross 1985).

It is evident that we are a long way from understanding the nature of the near-star gas flows in these mass losing stars.

(c) Application to α Ori

Now let us consider α Ori as a particular, well-observed, example. For reasonable parameters ($\dot{M} \approx 2\times10^{-6} M_{\odot}$ yr^{-1}, $L \approx 2\times10^{5} L_{\odot}$, $T_{eff}=3600$K, $v=8$km s^{-1}) we find $\Delta a = 65\text{Å}\ f_{-4} s(R_{*}/r_1)$. It is clear that *if* grain formation does not take place until, say, $r_1=6.5R_{*}$ (the minimum distance at which *dirty* silicate grains can survive), then (from eq. (1)) the resulting grains must be *very* small: $a<10$Å. In fact, infrared interferometric observations (McCarthy, Low, and Howell 1977; Sutton 1977; Howell, McCarthy, and Low 1981; Bloemhof, Townes, and Vanderwyck 1984) have been interpreted as showing that grain formation around α Ori does not occur within $\sim 10R_{*}$. The observations of Bloemhof *et al.* appear to indicate that the peak 10μm emission occurs approximately 0.9 arcsec from the star -- 40 stellar radii (for an assumed stellar angular diameter of 0.046 arcsec). On the other hand, scattering of starlight by circumstellar dust has been observed (McMillan and Tapia 1978), which requires the grains to be at least ~ 100Å or so in size. Thus we conclude that one or more of the assumptions made above must not be correct. It appears most likely that the assumption of a spherically-symmetric, steady outflow is unrealistic, and that the actual gas flow in the grain-forming region is time-dependent and possibly not spherically-symmetric. This of course is a serious complication, and one which poses a serious obstacle to progress in understanding the grain formation in this outflow.

Even so, it is difficult to see how grain nucleation and growth can be deferred until the gas reaches such large distances from the star. One possibility, of course, is that the outflow is strongly time-dependent, with little grain formation at the present time. At a velocity of 8km s^{-1}, the time scale for flowing one stellar radius is ~3 year, so that this interpretation would suppose that the star last produced dust a few decades ago. In this connection, it may be noted that the dust emission around α Ori appears to be asymmetric: Bloemhof *et al.* report

greater emission on the west side of the star. Furthermore, two distinct velocity components are observed in the outflow, with a $14 km s^{-1}$ component present exterior to the $8 km s^{-1}$ component (the 8 and $14 km s^{-1}$ components have CO rotational temperatures of 200 and 70K, repectively; Bernat *et al.* 1979), suggesting that the outflow properties have changed within the past 1000 years (Ridgway 1981).

Another possibility for trying to understand the peaking of the $10 \mu m$ emission at such large distances from the star is the following idea: the grains may nucleate relatively close to the star, as "clean" silicate grains. After the nuclei are present, grain growth may proceed in a self-limiting fashion: when the growing grain incorporates an "impurity" from the gas which enhances the grain absorptivity in the $\sim 1 \mu m$ region, the grain may heat up and begin evaporating atoms from the surface until it succeeds in removing the "impurity". The grain can obviously tolerate greater degrees of absorptivity as it is carried farther and farther from the star, until at $\sim 10 R_{*}$ it can exist in the fully dirty form. By this means grain nucleation can be carried out relatively close to the star, but grain growth will not be complete -- and the grains will not have attained their maximum absorptivity -- until the material has reached about 10 stellar radii from the star. This effect evidently helps in reconciling our theoretical expectations with infrared observations, though it seems incapable of accounting for the peaking of infrared emission at $30 R_{*}$ as reported by Bloemhof *et al.*

4. Summary

Based on the above, we see that our understanding of the grain formation phenomenon is extremely limited: the optical properties of small clusters are uncertain; the molecular physics of cluster nucleation and growth is poorly understood; and the properties of the gas flows within which the nucleation occurs remain mysterious. Much remains to be done on both the observational and theoretical fronts.

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Observations and Theories of Interstellar Dust

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Introduction and Disclaimer: I will try to summarize the observational properties of dust, as based on (1) the extinction over a factor of 100 in wavelength (0.1 μm - 10 μm), (2) on polarization, both linear and circular, (3) on rather narrow emission and absorption features in the spectrum, and (4) on reflection nebulae. I will then discuss theories. Clearly, I cannot mention much of the vast literature which is relevant. There are reviews in Savage and Mathis (1979), Stein and Soifer (1983), and Draine (1984). To the many workers in the field whose papers I will fail to cite, I say: please don't feel slighted; you have plenty of company.

It is essential to realize that the words "interstellar dust" refer to different materials when they refer to the diffuse ISM, to the outer edges of dense clouds, or to the dark central regions of those clouds. There are obvious observational selections which make it difficult to study dust in dense regions. Most of what I will say refers to dust in diffuse regions, which I will call "diffuse dust".

I. Observátions

A. Extinction. There is very good agreement on a "standard" extinction law for diffuse dust for $\lambda > 0.3$ μm. In dense regions, extinction for $\lambda > 0.55$ μm seems to be the same as for diffuse dust,but the value of $R(V)$ ($= A(V)/E(B-V)$) increases from the diffuse ISM value of 3.1 to 4 or 5. The change seems to be in the B magnitude, in the sense that the extinction becomes more grey. In the IUE ultraviolet, the situation is quite different: there are certainly real variations of the extinction even in the diffuse ISM, especially for $\lambda < 0.16$ μm (Massa et al. 1983; Witt et al. 1984a). These variations are often shared by all stars in a common region of the sky. The changes in extinction from one star to another have a universal wavelength dependence, suggesting that a single grain population is responsible for the far-UV rise (Greenberg and Chlewicki 1983; Massa and Savage 1984). The famous λ2175 "bump" is the only extinction feature in the whole visual-UV region (I am not considering the diffuse interstellar bands, which are likely produced by some material associated with dust). Unpublished work by E. L. Fitzpatrick and D. Massa (private communication) show that the wavelength of the maximum of the bump is exceedingly constant from direction to direction, while the width and strength of the bump vary significantly. This behavior is not at all like that expected from graphite; more about this later...

The only other spectral absorption features are in the near-infrared (NIR): the 9.7 μm "silicate" feature, which is matched well by amorphous silicates but somewhat better by the absorption in the oxygen-rich star μ Cep (Roche and Aitken 1984). There is a 20 μm absorption feature which is also present in

silicates. A 3.4 μm absorption is weak but consistent with absorption by C-H stretching. The absorption coefficients of individual hydrocarbons vary greatly, and only tiny amounts of some substances could produce the entire 3.4 μm band, while other materials would require most of the cosmically available carbon in order to have sufficient strength (Duley and Williams 1979). The 3.4 μm absorption is seen only when there is a huge amount of visual extinction, such as A(V) = 25 - 40 mag towards IRS 7 near the galactic center (Jones et al., 1983; Allen and Wickramasinghe 1981). We happen to be viewing the galactic center through only diffuse ISM, so the 3.4 μm band is presumably found in standard diffuse dust.

There is an absorption feature at 3.07 μm which does not occur in diffuse dust. It is sometimes not visible until A(V) = 25 mag (Harris et al. 1978), but it can appear at A(V) = 4 - 6 mag (Whittet et al. 1983). It can be fitted very well by solid water and ammonia ices (Hagen et al. 1983). There is also a 4.67 μm feature in very dark clouds which is presumably caused by solid CO (Lacy et al. 1984). Hence, there is no doubt that deep within dark clouds the grains have coatings of ices.

Emission features are observed at 3.3, 3.4, 6.2, 7.6, 8.8, and 11.9 μm in such diverse sources as some Seyfert I galaxies, planetary nebulae, and stellar sources deep within molecular clouds. There is a good review by Aitken (1981).

Linear polarization caused by alignment of grains shows a maximum at a wavelength, λ(max), which varies from star to star. It is in the range 0.4 to 1.0 μm, with an average of 0.55 μm. An empirical law (Wilking et al. 1982) fits the form of p(λ) very well. There is a good linear correlation between λ(max) and R(V) (Whittet and van Breda 1978), understood in a reasonable but qualitative way by the idea that both large λ(max) and R(V) are associated with particles which are larger than average (but see Chini and Kruegel 1983 for a note of caution on this point). There is no correlation between p(max) and E(B-V), except that their ratio never exceeds 9% per mag. This fact is easily explained: a tangled magnetic field or imperfect grain alignment can easily lower p(max)/E(B-V). The largest values of p(max)/E(B-V) must be associated with those directions with the most uniform magnetic field and perfect alignment. The observed maximum value implies almost perfect spinning alignment (Greenberg 1968).

The 9.7 μm "silicate" absorption band shows very strong linear polarization in some cases, such as the Orion BN object. The significance of this fact is that the grains responsible for the 9.7 μm band must be elongated and aligned.

Circular polarization provides a powerful diagnostic regarding those grains which are aligned (but, of course, only those) because it goes through zero at a wavelength λ(cir) which is quite sensitive to the dielectric constant of the material. Observations (Martin and Angel 1977) show that λ(cir) = λ(max), the wavelength at which linear polarization is a maximum. Martin (1974) showed that this condition implies that the polarizing material is a dielectric, with a real index of refraction and no

true absorption, if the index of refraction is independent of wavelength. The material magnetite has an index of refraction which varies with λ in such a way that at 0.55 μm, it would have $\lambda(\text{cir}) = \lambda(\text{max})$. However, the condition is met for stars which have different values of $\lambda(\text{max})$, and magnetite would not provide the observed condition for other wavelengths. Thus, the grains which provide the polarization have an albedo of almost unity. As we shall see, this fact puts powerful pressure on theories of grains.

Reflection nebulae and the diffuse galactic light can in principle provide information about grains, but unfortunately the interpretation of observations is highly dependent on the unknown geometry of the nebula. The most interesting observation is that there is an excess of emission in the NIR, probably extending into the red spectral region (Sellgren 1984, Witt et al. 1984b). I would guess that it extends into the IRAS 12 and 25 μm channels as well. It is presumably caused by either a fluorescence (excited by a UV stellar photon) or by the heating of very tiny grains by single UV photons, followed by radiative cooling. The spectrum of the excess emission, and its variation with spectral type of the exciting star, will be an interesting diagnostic of grains.

There are other diagnostics I will not discuss. One is the spectrum of the far infrared (60 - 200 μm) emission from the grains heated by the galactic starlight. The spectrum depends on the dielectric properties of the materials through the absorption of the visual/UV and the emissivity in the FIR. The formation and destruction of grains, and the depletions of elements from the gas phase of the ISM, also are important clues as to the kinds of particles which ought to be present in space.

II. Theories of Grains

There are at least four "complete" theories of grains which claim to explain the entire range of observable wavelengths (0.1 - 20 μm). They have one feature in common, in my opinion: each is in conflict with at least one observation. Possibly the real answer is a combination of some of these ideas, plus, I suspect, several concepts which no one has thought of yet.

I discuss the theories in turn, followed by a contrast of the two most commonly discussed ones.

A. F. Hoyle and N. C. Wickramasinghe (1982) advocate a mixture of anhydrous biological material, plus graphite for the λ2175 bump. Jabir, Hoyle, and Wickramasinghe (1982) give a specific list of materials in the model, but the ingredients seem to vary from time to time. The only concrete objection I am aware of (Whittet 1984) is that the model uses an order of magnitude more phosphorus than is cosmically available.

B. W. W. Duley, T. J. Millar, and associates (e. g., Duley and Najdowsky 1983) explain the extinction with various metallic oxides and amorphous carbon. The λ2175 bump is caused by transitions of surface oxygen ions on tiny (10 Angstrom) MgO crystals. The tiny size is required because only surface atoms

carry the transition (in fact, bulk MgO has a very strong absorption at 0.164 μm which is not seen). There are also SiO and FeO grains which are large (0.1 μm), elongated, and aligned in the galactic magnetic field. These grains provide the polarization. The strongest laboratory support of this model is the study (MacLean et al. 1982) of blue flourescence radiation produced by UV of various wavelengths incident upon MgO crystals. The blue emission is a maximum when the UV is at λ2200. A direct measurement of the λ2175 absorption would be much more convincing.

It seems strange to me that one has tiny MgO and large SiO and FeO particles. Another serious objection to this theory is the strong polarization of the BN object at 20 μm (Knacke and Capps 1979). The polarization is caused by FeO and SiO; MgO cannot produce polarization because its crystals are cubic and are therefore too symmetrical. SiO has no bands at 20 μm, and FeO provides much less absorption than MgO at 20 - 25 μm (Brehat et al. 1966).

C. J. M. Greenberg and his associates have developed a three-component model (e. g., Greenberg 1984a,b). The constituents are: (1) A population of tiny grains, probably silicates, to provide the steep rise of extinction with 1/λ at λ < 0.16 μm. (2) Small graphite grains (or something similar) to provide the λ2175 bump. (3) Mantle-coated silicate grains to provide almost all of the extinction from 0.3 μm through the visual/NIR. The mantles, which occupy 90% of the volume, are assumed to be the "yellow stuff" refractory residue left behind after warming UV-photolyzed ices of CO, water, ammonia etc., to a few degrees Kelvin. The free radicals in the ices react and produce the yellow material which is stable at room temperatures. These reactions provide the gas-phase molecules which are observed in dark clouds. The observations of the 3.07 μm absorption band strongly indicate that icy mantles do form within dark clouds; the question is how much of the refractory residue of the mantle can remain after the grain has been injected into the diffuse ISM and has been subjected to shocks and other harsh environments.

D. Mathis, Rumpl, and Nordsieck (1977; hereafter MRN) have two populations of bare refractory grains for the diffuse ISM. One component is graphite; the other is silicates. Both have a power-law size distribution in sizes. There is a rather arbitrary cutoff in sizes at both ends. Originally, the smallest size was assumed to be about 0.005 μm because the data were insufficient to determine the distribution of smaller sizes. The observed excess NIR emission of reflection nebulae suggests that the smallest particles might be about 0.001 μm, which makes them molecules rather than grains. The largest particle size is also rather arbitrary, but about 0.25 μm or so fits the extinction and polarization quite well. Increasing the largest size for silicates fits observed extinction in the edges of dark clouds. Recently, the optical constants of graphite and silicates have been rediscussed by Draine and Lee (1984), and any predictions of the MRN model should be made with their constants.

The MRN model almost surely needs modification regarding the origin of the $\lambda2175$ bump. MRN requires the bump to be produced by a size distribution of graphite particles rather than entirely by small ones. The maximum is shifted about 0.01 μm to longer wavelengths by the contributions of small but not tiny (e.g., 0.02 μm) particles, which also contribute scattering in the $\lambda < 0.15$ μm region. This picture makes the constancy of the wavelength of the maximum of the bump, and the lack of correlation of the bump strength with the $\lambda < 0.15$ μm extinction, hard to understand (Greenberg and Chlewicki 1983).

I think that two recent ideas probably go a long way towards clearing up the problems with the $\lambda2175$ bump. They are theoretical calculations by Leger and Puget (1984, and preprints) and laboratory work by Sakata and coworkers (1983, 1984). In the Sakata et al. work, methane is subjected to a discharge, and the products are quenched onto a substrate. The residue is called QCC ("quenched carbonaceous composite"). The QCC shows both the $\lambda2175$ bump and absorption features at most of the wavelengths of the NIR emission bands in the ISM. The Leger and Puget theory suggests that mixtures of polycyclic aromatic molecules of molecular weights of about 50 or so, which I think of as pieces of graphite, should produce the emission features and the NIR excess in reflection nebulae. However, it is somewhat obscure to me how the width of the bump can vary much with the QCC or polycyclic aromatics ideas.

It has always been difficult to understand how carbon can be annealed into graphite in the brief time it spends as a hot solid in a carbon-star atmosphere. Annealing in interstellar space seems even more difficult. Therefore, I find the suggestions outlined above very appealing, and feel that MRN should be modified to include the polycylic aromatics, or whatever QCC is.

Observational confrontation of MRN and Greenberg theories is possible because of the predictions of the nature of visual extinction. The reasoning is that the circular and linear polarization, taken together, show that the polarizing material is a dielectric. If there is only one kind of grain providing the extinction, as in the Greenberg theory, then the visual albedo must be almost unity (see Greenberg 1984b). Using the optical constants of Draine and Lee (1984), I estimate that less than 7% of the extinction at $H\alpha$ is provided by the graphite required to produce all of the bump, and I suspect that QCC or polycyclic aromatic molecules probably have about the same absorption as graphite because of a similar chemical structure. Thus, the albedo of the Greenberg theory should be 0.93 because only the "graphite" is providing true absorption. Yet, we know that H II regions have fairly large absorption of their Balmer lines, as judged from the $H\alpha$/radio continuum ratios (e.g., Israel and Kennicutt 1980). If there were just scattering, the line photons would escape, and we would see no reduction in line strength. Thus, the albedo at $H\alpha$ must be appreciably different from unity, and 0.93 is nowhere near different enough.

Similar reasoning applies to reflection nebulae; most analyses suggest a visual albedo of 0.6 - 0.7. The MRN predicts an albedo of about 0.55 at Hα and 0.61 at V.

Another point of disagreement between MRN and Greenberg is whether the grains in the outer parts of dark clouds are larger because of coagulation (MRN; see Mathis and Wallenhorst 1981) or accretion of mantles (Aannestad and Greenberg 1983). Accretion is a reasonable idea, and must certainly take place beyond some point in the cloud. However, observations of two stars embedded in clouds, ρ Oph and NU Ori (Shull and van Steenberg 1985) show that the ratio of the column density of H I to extinction, N(H I)/A(V) is greater for these stars than for the average ISM. In other words, the extinction cross section per neutral H drops as we go into the cloud. This is predicted by coagulation (Jura 1980), becuase larger grains are less efficient absorbers. The fact that only two stars show the increase does not imply that others do not show coagulation. In dark clouds, most H is molecular, which IUE cannot detect. If accretion were the true situation, the conversion of atomic H to molecular alone should decrease N(H I)/A(V), since the cloud material contributes dust without atomic H. Adding new material to each grain, thereby increasing A(V) for the fixed number of grains per H nucleus, makes matters so much worse. Thus, accretion in the outer parts of clouds predicts the wrong sign of the observed extinction per H nucleus.

Supposedly the wavelength dependence of linear polarization is a strong point in favor of the Greenberg model (Aannestad and Greenberg 1983). I have a poster in this workshop giving what seems to me to be a natural and quantitative explanation of both the shape and changes from region to region of the linear polarization. Since it hasn't been properly refereed, I will not comment on it further. I invite criticisms of the poster.

Overview: I close with the thought that there have been great strides in the understanding of the nature of dust in the past ten years. I feel that the new ideas regarding QCC and polycyclic aromatic hydrocarbons are very exciting. I suspect that no one theory will emerge as the "winner", and that the true one has yet to be formulated.

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SHOCK PROCESSING OF INTERSTELLAR GRAINS

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I. INTRODUCTION

There is strong evidence for the destruction of dust grains in fast shock waves in the interstellar medium (ISM). This talk will discuss some of this evidence and will review the mechanisms by which the grains are destroyed in shocks. Grain growth in shock waves is a more controversial subject, although it is potentially as important as the destruction processes. A few comments on growth mechanisms will be made at the end of this talk.

II. IMPORTANCE OF SHOCKS

The shocks most effective at destroying grains are those with velocities in the range 30-400 km s^{-1}, propagating through diffuse interstellar clouds ($n_H \approx 10$ cm^{-3}) or intercloud matter ($n_H \approx 0.2$ cm^{-3}) with magnetic fields of 1-3 μG. These velocity limits are not precise; shocks slower than about 30 km s^{-1} are ineffective at destroying grains, while shocks faster than 400 km s^{-1} are too infrequent to be important. Grain destruction in shocks has been considered by many authors, including Cowie (1978), Shull (1977, 1978), Barlow (1978a,b,c), Draine and Salpeter (1979), and most recently by Seab and Shull (1983). These destruction models are relatively independent of the source of the shock wave, except insofar as the source determines the shock parameters.

The most important source for destructive shocks is probably supernova remnant (SNR) blast waves (Draine and Salpeter 1979), with cloud-cloud collisions being of lesser importance. The shock models can also be applied to stellar wind shocks (Castor, McCray, and Weaver 1975), and to Herbig-Haro

Objects (Dopita 1978; Raymond 1979; Brugel et al. 1982) and pre-main-sequence outflows in molecular clouds (Shull and Beckwith 1982). It should be noted that grain destruction within a radiative shock returns certain elements to the gas phase, where they increase the cooling and alter the structure of the post-shock region.

The importance of shock processing during the life of an interstellar grain can be estimated from the timescale for a typical grain to be hit by a fast shock, which follows from the supernova rate for the galaxy and the structure of the ISM. Consider a typical SNR with an expansion velocity of 100 km s^{-1} and a radius of 30 pc. If the mean interval between supernovae is 50 years throughout the galaxy, the shock time for a grain is approximately the supernova interval divided by the fraction of the galaxy occupied by the SNR:

$$t_{shock} = t_{SN} x (V_{gal}/V_{SNR})$$

$$= (50 \text{ yr})[(830 \text{ kpc}^2)(200 \text{ pc})/(4 \pi/3)(30 \text{ pc})^3] = 7\times10^7 \text{ yr}$$

More accurate calculations for the three-phase ISM (McKee and Ostriker 1977) give a time of 10^8 years for a grain to be hit by a shock 100 km s^{-1} or faster. This time should be compared to the several by 10^9 years calculated by Dwek and Scalo (1980) for injection of new grains into the ISM. The time for astration, or destruction by incorporation into stars, is about the same (Greenberg 1984). Therefore, a typical interstellar grain is hit by 10-20 fast shocks if it lives long enough for astration. Grains in the less dense intercloud medium will be hit even more often, on the order of every 10^7 years. Because of this high frequency of shocks, the properties of the ISM grain population will be strongly influenced and perhaps determined by the results of shock processing.

III. EVIDENCE FOR SHOCK PROCESSING

The first evidence suggesting that grains are destroyed in shocks came from the observation (Routly and Spitzer 1952; Siluk and Silk 1974) that high velocity (20 - 100 km s^{-1}) interstellar clouds exhibit a statistically higher

Ca II/Na I ratio. Shull, York, and Hobbs (1977) showed that Si and Fe abundances were also significantly greater in high velocity clouds. These observations have been interpreted as evidence for shock destruction of Ca, Fe, and Si atoms in grains by sputtering and grain-collisions (Jura 1976; Spitzer 1976; Shull 1977). These same shocks are also responsible for producing the clouds' observed velocities.

Further abundance studies with the Copernicus satellite (Fig. 1) showed that clouds with velocities greater than 100 km s^{-1} appear to have nearly cosmic abundances of Fe and Si, implying that most of the grain material has been destroyed. The cloud Doppler velocity provides a lower limit on the actual shock velocity, owing to projection effects and to cloud deceleration since the time the shock destruction began. These ultraviolet observations are significant for establishing the link between shocks and grain destruction, since silicon is commonly believed to be a major component of grain material (see Mathis review talk in this volume).

There exist two weaker pieces of evidence for grain destruction. The first is the correlation between theoretical shock-processed UV extinction curves and IUE satellite observations in lines of sight associated with supernovae (Seab and Shull 1983). These lines of sight show stronger than usual 2175 Å extinction features and enhanced far-UV extinction rises (Fig. 2). However, other explanations for these trends are possible. Second, Si or Fe abundance surveys by the Copernicus (Savage and Bohlin 1979) and IUE (Shull and Van Steenberg 1982, 1985) satellites have uncovered a correlation between depletion and mean line-of-sight density (Fig. 3). This correlation could result from preferential grain destruction in the less dense regions or from grain growth in the more dense regions. Alternatively, the apparent correlation might simply be a sampling artifact of the ISM cloud structure (Spitzer 1985).

Nevertheless, most lines of evidence point to significant grain destruction in high velocity clouds. Each piece of evidence requires a theoretical understanding of the fate of grains in interstellar shocks.

IV. GRAINS IN SHOCKS

a) Shock Structure - Radiative Shocks

The canonical grain-destroying shock modeled by Seab and Snull (1983) is a $V_S = 100$ km s^{-1}, plane-parallel, steady-state radiative shock propagating into a region of density $n_0 = 10$ cm^{-3} and magnetic field $B_0 = 1$ μG. Following a radiative precursor (Shull and McKee 1979), this gas experiences a collisionless shock layer ($N_H < 10^{14}$ cm^{-2} for electron-ion equilibration), followed by a thick ($N_H \approx 5\times10^{18}$ cm^{-2}, or spatial thickness 10^{15} cm) post-shock cooling region. It is in this cooling region that most of the grain destruction occurs. To 25% accuracy, the thermal gas pressure, nT, is constant in the downstream region, so that as the temperature falls, the density rises. Using the Lagrangian formulation, following a parcel of shocked gas as it flows downstream from the front, one may convert between post-shock column density and flow time, $N_H = n_0 V_S t$.

Figure 4 shows the temperature and density structure of a 100 km s^{-1} shock. Viewed in the frame in which the front is at rest, pre-shock gas of density n_0 streams toward the front at velocity V_S. Immediately behind the front, the density n jumps to about $4n_0$, and the gas velocity v relative to the shock front drops to about 0.25 V_S ($nv = n_0 V_S$ by mass conservation). The post-shock temperature T_S is determined by the shock's ram pressure, $kT_S = (3/16)(\mu V_S^2)$, and is essentially independent of the pre-shock density or ambient temperature. For a 100 km s^{-1} shock, $T_S \approx 1.4\times10^5$ K. Cooling in this hot post-shock gas occurs primarily by collisional excitation of resonance lines of H, He, carbon and oxygen. The ionizing radiation from this hot zone affects the shock structure in two ways: (1) for $V_S > 110$ km s^{-1}, the pre-shock medium is fully ionized by the radiative precursor; and (2) downstream absorption of the ionizing radiation extends the hydrogen recombination zone and creates a plateau in the temperature and density curves. This plateau occurs at T ≈ 5000-10,000 K, after $N_H \approx 10^{18}$ cm^{-2}. Finally, at $N_H \approx 5\times10^{18}$ cm^{-2}, the ionizing radiation is nearly absorbed, and the temperature is cooled below a few hundred degrees by collisional excitation of infrared fine structure lines of C II (158 μm), O I (63 μm), and Si II (34.8 μm).

b) Grain Motion in Radiative Shocks

The large inertia of dust grains ensures that they will flow unimpeded through the thin collisionless shock and into the hot post-shock gas. Because the grains are charged, they gyrate in the magnetic field. At the shock front, a grain's pre-shock velocity of V_s relative to the front is converted into a gyromotion of $0.75V_s$ about a guiding center drift of $0.25V_s$. The details of the grain motions are determined by the electric field generated by the plasma flow through the magnetic field and by the thermal charging of the grains -- see Shull (1977, 1978). As the magnetic field is compressed downstream together with the plasma, grains are betatron accelerated to higher gyrovelocities by conservation of their magnetic moments, while their guiding center motion is locked to the gas flow. Plasma coulomb and collisional drag forces decelerate the grains; these forces are more effective on small grains, owing to their larger area-to-volume ratios.

Model results show that the large (0.25 μm radius) grains can reach gyrovelocities of about $2V_s$, or 200 km s^{-1} for the canonical shock. The gyromotions of the smallest (<0.01 μm) grains are damped out early in the post-shock layer before reaching the strong cooling zone. Small grains are thus not betatron accelerated to high velocities. Figure 5 shows representative gyrovelocities for large and small grains of different types.

c) Grain Destruction Mechanisms

Large grains gyrating at over 100 km s^{-1} bump into things frequently. Collisions with He nuclei at 100 km s^{-1} carry collision energies of 200 eV, whereas sputtering thresholds for silicates are around 23 eV. The sputtering erodes away the outer layers of large grains, but leaves the inner cores intact. This sputtering is non-thermal, since it is driven by the velocity of the grains striking the He nuclei. Sputtering by H nuclei is much less efficient, contributing only about 10% of the total. In shocks below 200 km s^{-1}, sputtering due to the thermal velocities of H and He is insignificant.

A collision between two grains of comparable size at 100 km s^{-1} velocities will probably vaporize both grains, including their cores. Some fragmentation might occur, but the importance of the fragmentation process is

limited by the requirement of matching the observed gas-phase abundances in Fig. 1. Vaporization in grain-grain collisions is dominated by large grains striking medium-sized grains, which are favored because they are more abundant (Mathis, Rumpl, and Nordsieck 1977 -- hereafter MRN). The threshold energies in the center-of-mass frame prevent collisions with the smallest grains from vaporizing large grains.

Shock models (Seab and Shull 1983) show that about 50% of the grain material can be returned to the gas phase in a 100 km s^{-1} diffuse cloud shock, in general agreement with Draine and Salpeter (1979) and Shull (1978). The Seab-Shull results are an improvement over the earlier work since they use a full MRN size and composition distribution to calculate grain-grain collision effects, and because their code allows the shock's cooling structure to be affected by the heavy elements released by grain destruction.

The principal destruction mechanisms in steady-state radiative shocks depend primarily on the betatron acceleration of the grains, and are therefore more effective for large grains. Small grains survive these shocks, but they are preferentially destroyed by thermal sputtering in fast adiabatic shocks.

d) Grain Destruction in Adiabatic Shocks

Shocks with $V_s > 200$ km s^{-1} cannot be treated with the steady-state radiative shock models discussed above. The cooling time for these shocks usually exceeds the expansion time, R_s/V_s, of the generating SNR, so that the time-dependent pressure drop of the expanding remnant must be considered. The effect of the pressure drop is to partially suppress the betatron acceleration of grains. Instead, thermal sputtering in the $>10^6$ K post-shock gas becomes the dominant grain destruction mechanism, as the thermal energy of the shocked gas increases above the sputtering threshold. Grains up to several 100 Å size that survive slower shocks will be destroyed in these fast shocks.

e) Timescales for Grain Destruction

Calculating galactic averages for shock destruction rates is a formidable problem. It involves modeling the occurrence and evolution of supernova blast

waves and cloud-cloud collisions in the galaxy, together with models for the ISM structure and grain destruction fractions in shocks. Several authors have attempted this sort of modeling. Dwek and Scalo (1980) find grain lifetimes of 10^9 years, somewhat less than their injection rates of new grains into the ISM. They conclude that heavy element depletions greater than 30% can only explained by grain accretion processes in the ISM. Draine and Salpeter (1979) obtain lifetimes nearer 10^8 years, which makes the requirement of in situ grain growth even stronger. Greenberg (1984) suggests a scenario for grain evolution in the galaxy, but he underestimates the effectiveness of shock destruction.

Seab, Hollenbach, McKee, and Tielens (see abstract, this volume) have undertaken a thorough analysis of the grain history and life cycle in the galaxy. Their preliminary results indicate grain lifetimes slightly over 5×10^8 years, nearly independent of size. Further work may modify this figure, particularly for the large grains.

These grain lifetimes present a problem for silicon depletion, since Si is a major grain constituent which is about 90% depleted in the diffuse ISM (Fig. 3). Since grain injection times are about 10^9 years, such large depletions would seem to require grain lifetimes of 10^{10} years. Three possible explanations for the discrepancy are: (1) grain injection rates are an order of magnitude larger, contrary to observations of the occurrence of supernovae and mass-loss in red giant winds; (2) grain destruction rates are an order of magnitude lower, which seems unlikely at this time; or (3) much of the observed grain mass is formed by some process in the ISM itself. As an example of the last process, we will next discuss grain growth in shocks.

V. GRAIN GROWTH IN SHOCKS

The standard sources for new grains in the ISM are: red giant winds, planetary nebulae, novae, and possibly protostellar nebulae or supernova ejecta. If grains form efficiently in supernova ejecta, then this source dominates red giant winds by a factor of three, with the other sources being less important (Dwek and Scalo 1980). As discussed above, the total injection rates from these sources are inadequate to explain the 90% depletion of Si in the diffuse ISM, given the current best estimate for destruction rates.

Grain growth behind shocks is a speculative field, since there is little data supporting such growth. It is difficult observationally to distinguish newly-grown grain material in a shock from grains swept up from the ambient medium (Dwek et al. 1983). Meyers et al. (1985) present data suggesting that some grain growth has occurred behind a 10 km s^{-1} shock towards ζ Oph; however the difficulty of the observation prevents their conclusions from being compelling.

Grain growth is more likely in low velocity (V_s < 30 km s^{-1}) shocks that are inefficient at grain destruction. In fast shocks, the grain velocities are well over sputtering thresholds, and the net effect will be to sputter away rather than add to grain surfaces. It is unlikely that the grains will sweep up much new material after they slow below sputtering thresholds. The plasma coulomb drag peaks when the grain velocity is comparable to the proton thermal velocity, and the gyration of the grain slows rapidly once it drops below its betatron-accelerated peak. However, even in fast shocks, grain growth may occur in the cool dense regions far downstream from the front.

A chemical question arises in this context. Approximately 10^4 hydrogen atoms will strike the grain surface for each atom of a refractory element. It is possible that this much H could inhibit grain growth by occupying all the available binding sites before a heavy element could stick. On the other hand, H_2 formation on grain surfaces could provide a "safety valve", or the ionization state of the heavy elements (C II, Si II, Fe II) and the grain charge could complicate the gas-grain interactions. Evidently further laboratory and theoretical work is needed on these questions.

Two scenarios have been proposed in which grains could form or grow behind fast shocks. The first occurs when a fast shock impinges on a dense cloud. The shock will decelerate quickly, so that the steady state shock destruction rates do not apply. Elmegreen (1981) calculates that the relative forward drift of grains can equilibrate with the deceleration of the shock to maintain part of the grain population at a fixed position behind the shock front where growth is possible. He suggests that centimeter sized grains can grow behind SNR shocks and potentially accumulate enough of the ejecta material to explain the isotopic anomalies observed in connection with interplanetary grains (see Kerridge review in this volume). Alternatively, Dwek has suggested that grains can nucleate and grow in dense clumps of

supernova ejecta plowing through a less dense ambient medium. Such newly formed grains will be protected by the density of the clump from destruction by the initial SNR blast wave or from reverse shocks.

These two growth mechanisms can potentially explain the observed isotopic anomalies in meteorites, provided that at least some grains survive long enough in the ISM for incorporation into the solar system. However, none of these growth mechanisms is likely to compensate for the large destruction rates calculated for radiative and adiabatic shocks. Unless substantial changes are made in the grain injection or destruction rates, then a new grain growth mechanism must be found. The best candidate may be grain growth in dark interstellar clouds (Draine 1984).

VI. CONCLUSION

Shock processing plays an important role in the life of a typical interstellar grain. Shocks of 100 km s^{-1} or greater can destroy about 50% of the grain material under appropriate pre-shock conditions of density and magnetic field. The destruction occurs by grain-grain collisions and non-thermal sputtering for steady-state radiative shocks ($30 < V_s < 200$ km s^{-1}) and by thermal sputtering for fast adiabatic shocks ($V_s > 200$ km s^{-1}).

The evaluation of the lifetime of grains against shock destruction depends on models of the ISM structure and on SNR evolution. Results from various authors give lifetimes between 10^8 and 10^9 years, compared to typical injection times for new grains of a few times 10^9 years. These numbers require that a major portion of the interstellar silicon bearing grain material must be formed by grain growth in the ISM. At the same time, the presence of isotopic anomalies in some meteorites implies that at least some grains must survive from their formation in SNRs or red giant winds through incorporation into the solar system. These requirements are not necessarily incompatible.

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FIGURE CAPTIONS

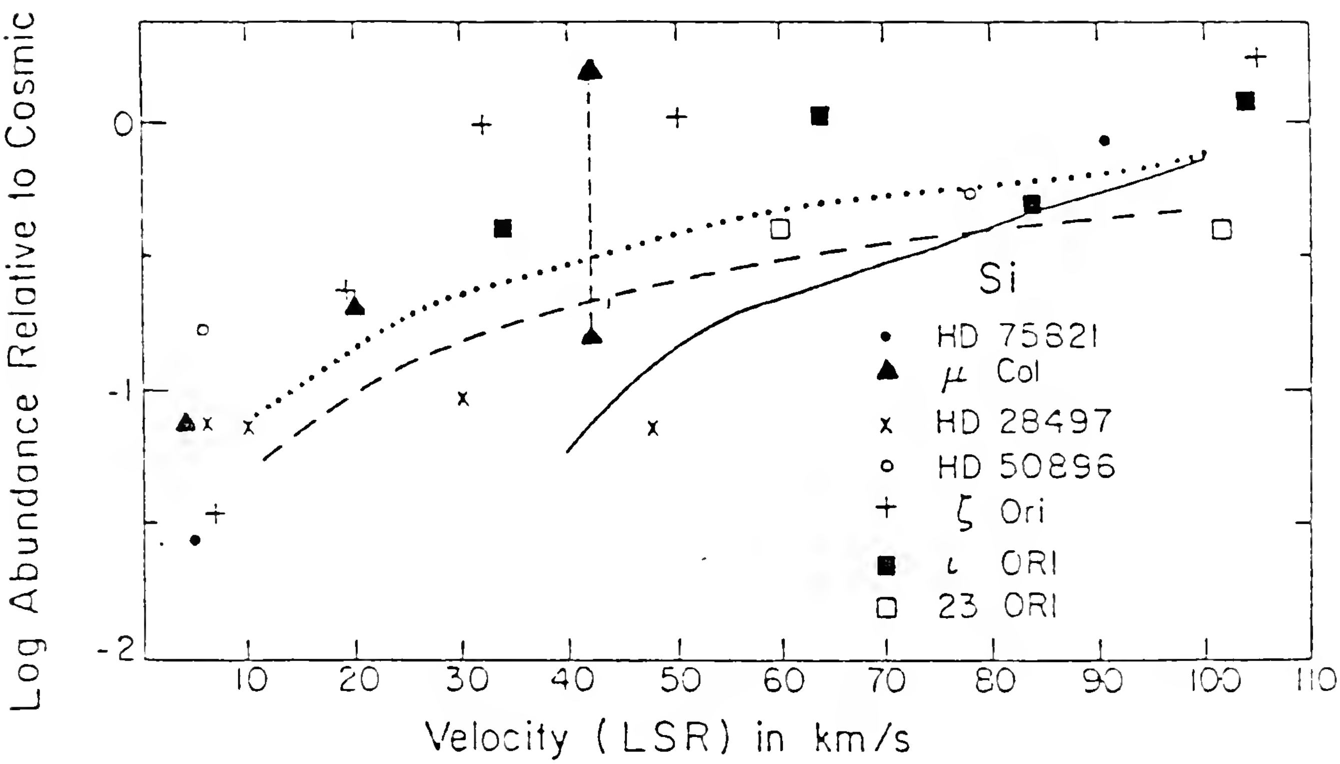
Fig. 1. Depletion of Si as a function of cloud radial velocity, compiled by Cowie (1978). The solid, dashed, and dotted curves show theoretical depletion curves from various authors.

Fig. 2. Normalized $E(\lambda-V)/E(B-V)$ selective extinction curves towards stars associated with SNRs (Seab and Shull 1983), compared to the "standard" interstellar curve of Savage and Mathis (1979). The stars HD 48099 and HD 48434 are near the Mon Loop SNR, while HD 72350 and HD 75821 are in the Vela SNR.

Fig. 3. Depletion correlations of interstellar Si and Fe from a preliminary sample of an IUE abundance survey (Shull and Van Steenberg 1982, 1985). Note the increased depletion, log δ, in lines of sight with higher mean density, $N(H_{tot})/r$.

Fig. 4. Temperature and density structure for a shock with V_s = 100 km s^{-1}, pre-shock density n_0 = 10 cm^{-3}, and magnetic field B_0 = 1 μG. Behind this shock, the thermal pressure, nT, is nearly constant, and the column density $N_H = n_0 V_s t$ in cm^{-2} is a factor of 10^8 greater than the time t in seconds.

Fig. 5. Grain velocities behind a 100 km s^{-1} shock (Seab and Shull 1983) for two grain sizes and for both silicate and graphite composition. The large grains (0.25 μm) experience betatron acceleration and reach large velocities, while the small grains (0.01 μm) slow down rapidly by collisional and plasma coulomb drag.



Log Abundance Relative to Cosmic
0
-1
-2
10
20
30
40
50
60
70
80
90
100
110
Velocity (LSR) in km/s
Si
HD 75821
μ Col
HD 28497
HD 50896
ζ Ori
ι ORI
23 ORI

Fig. 1

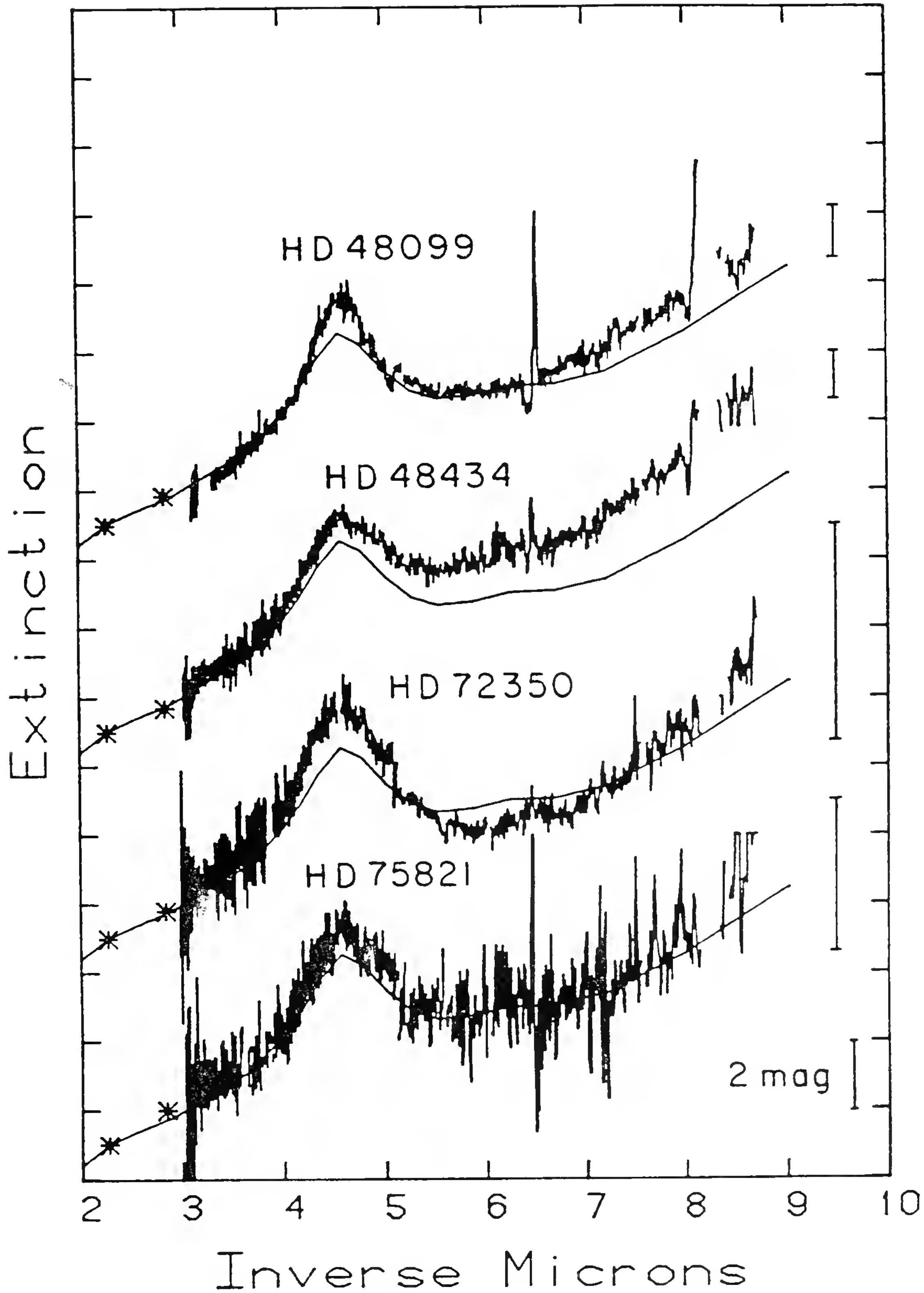

HD 48099
HD 48434
HD 72350
HD 75821
2 mag
Extinction
2
3
4
5
6
7
8
9
10
Inverse Microns

Fig. 2

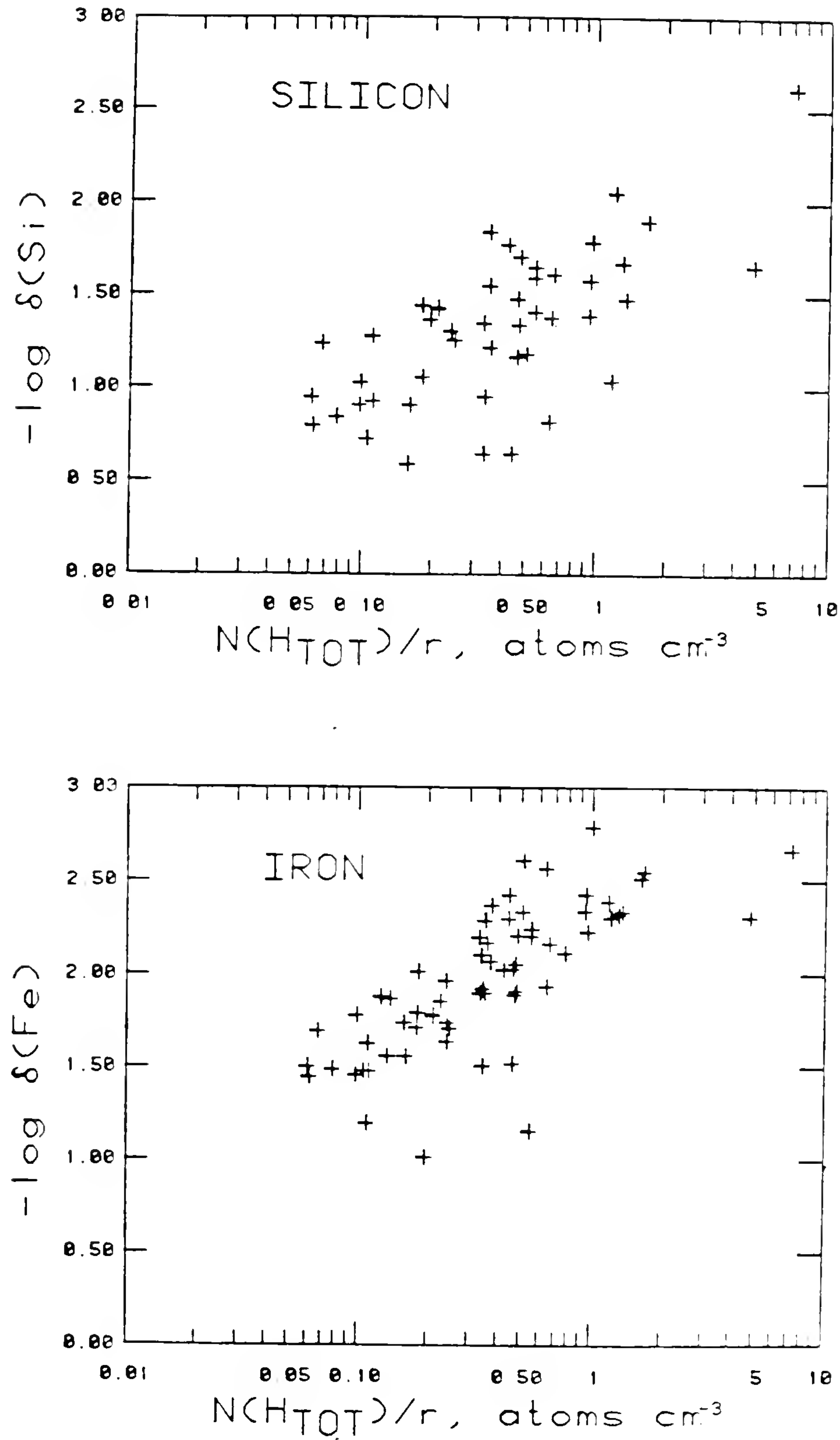
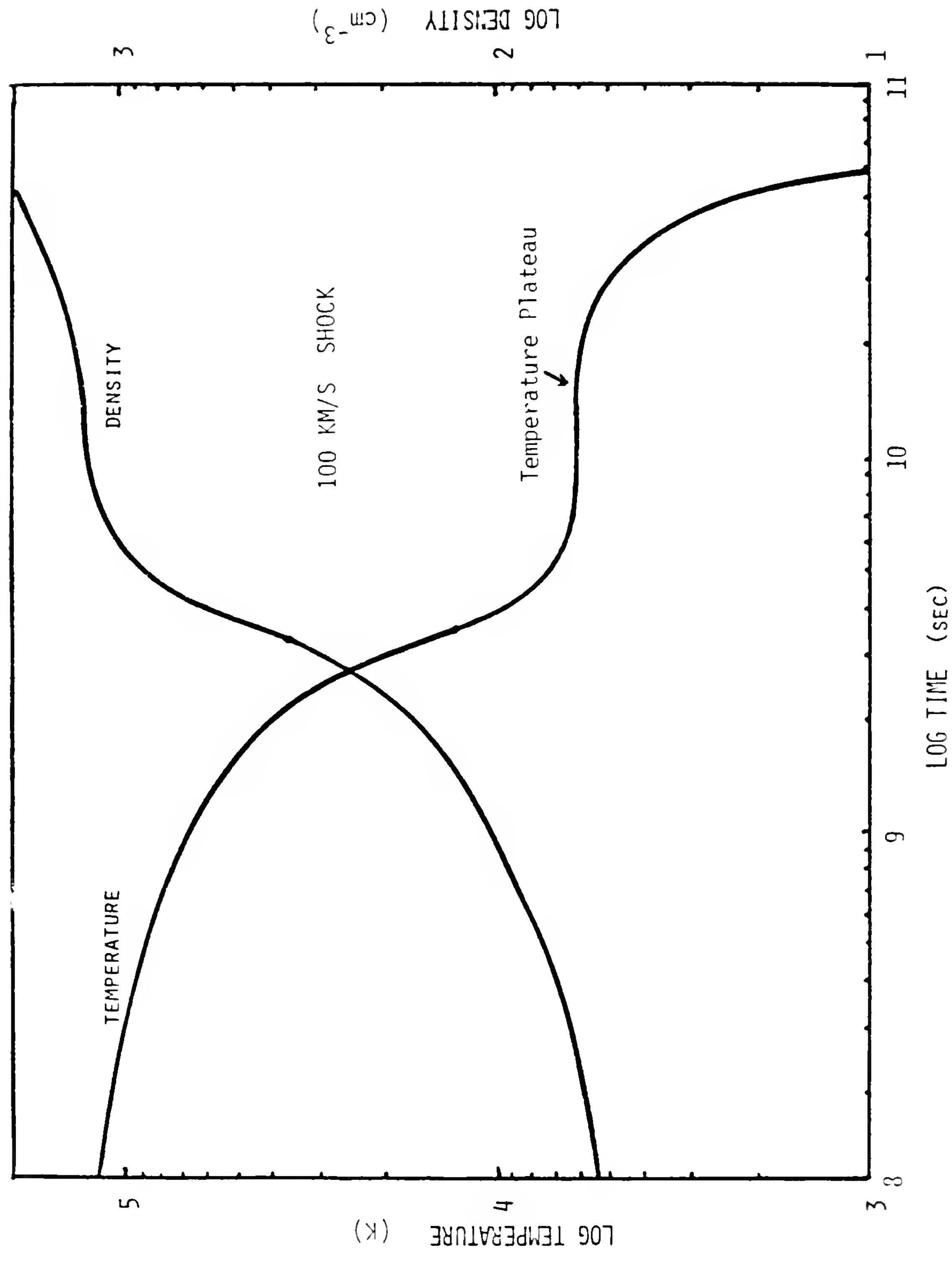

SILICON
-log δ(Si)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.01
0.05 0.10
0.50
1
5
10
N(HTOT)/r, atoms cm-3
IRON
-log δ(Fe)
3.03
2.50
2.00
1.50
1.00
0.50
0.00
0.01
0.05 0.10
0.50
1
5
10
N(HTOT)/r, atoms cm-3

Fig. 3



100 KM/S SHOCK
DENSITY
TEMPERATURE
Temperature Plateau
LOG TIME (SEC)
LOG TEMPERATURE (K)
LOG DENSITY (cm^{-3})
8
9
10
11
3
4
5
1
2
3

Fig. 4

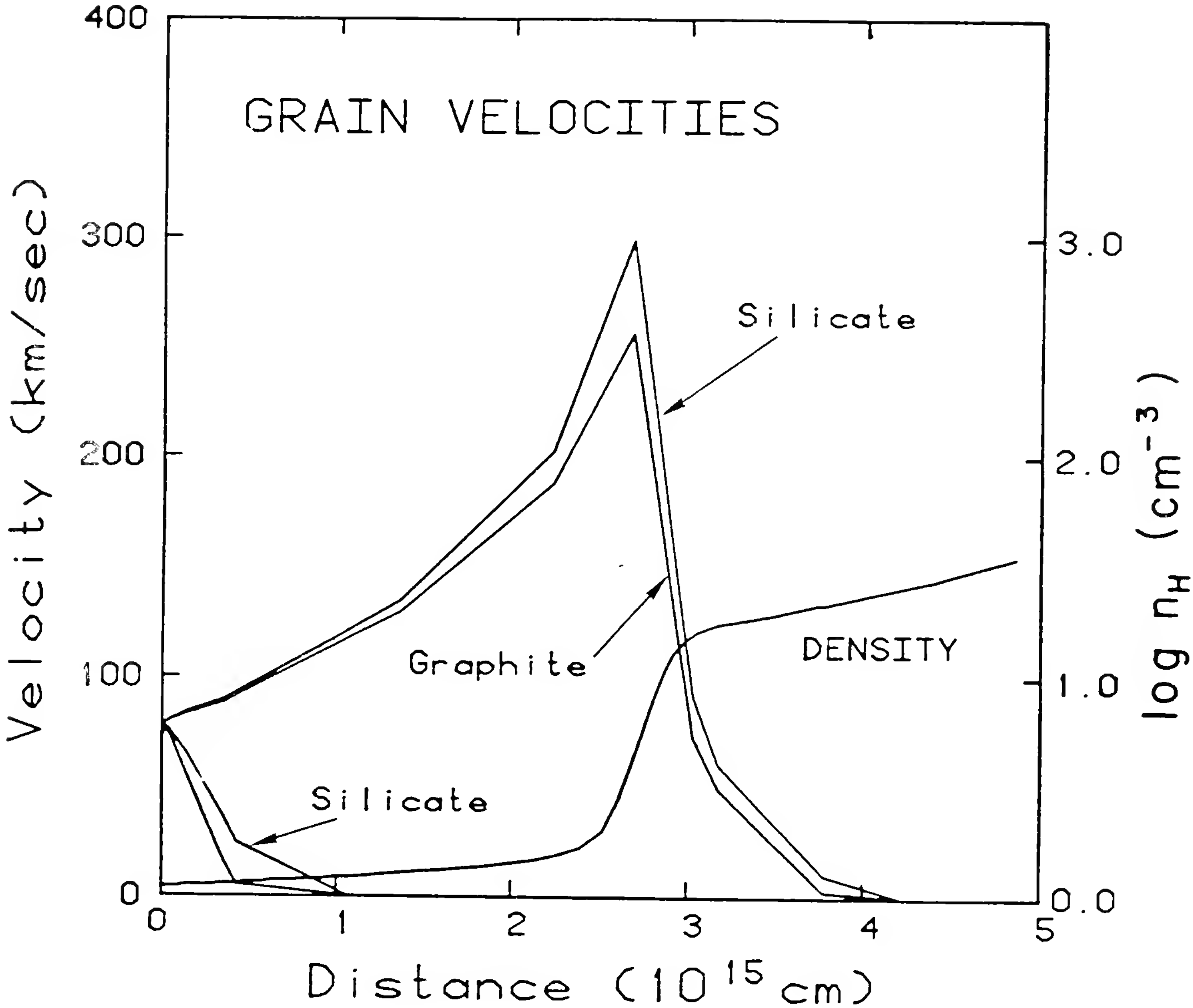

GRAIN VELOCITIES
Silicate
Graphite
DENSITY
Silicate
Velocity (km/sec)
log n_H (cm^{-3})
Distance (10^{15} cm)
400
300
200
100
0
3.0
2.0
1.0
0.0
0
1
2
3
4
5

Fig. 5

LABORATORY STUDIES OF INTERPLANETARY DUST

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LABORATORY STUDIES OF INTERPLANETARY DUST

I. INTRODUCTION

Interplanetary dust particles collected in three different ways are now available for laboratory study. Impact collectors flown on aircraft sampling the stratosphere have provided the most important source of (more or less) unaltered interplanetary dust material [1]. Larger cosmic particles have been recovered from sediments, both from the sea [2], and, most recently, from temporary glacial lakes in Greenland [3]. Finally, debris samples from impacting interplanetary particles have also been collected in experiments flown in earth orbit and returned to earth [4, 5, and 6b].*

This brief review treats only the analysis of dust particles collected in the stratosphere. These particles are the best available samples of interplanetary dust and have been studied using a variety of analytical techniques. The particles are systematically collected and curated by a group at the Johnson Space Center, Houston. Catalogs of the collections have been published and individual particles are made available to qualified investigators on request [8].

The stratospheric dust particles have been called by a variety of names (including the deserved description as "Brownlee particles") and a word about nomenclature is in order. In what follows, stratospheric particles whose major element compositions are similar to those of chondritic meteorites, are referred to as "interplanetary dust particles or IDPs." Some particles in this chemical class are demonstrably extraterrestrial. To facilitate discussion, certain IDPs have also been given individual names, e.g. Calrissian, Skywalker, etc. Particles in other chemical classes are not treated in this paper. Although some of them may be extraterrestrial, both man-made and natural contaminants are abundant in the non-chondritic chemical classes.

For a more complete view of IDPs and other cosmic dust particles the reader is referred to two reviews [9,10].

The following questions are addressed in this workshop paper:

1. Is it certain that chondritic stratospheric dust particles are extraterrestrial?
2. What are the general physical, chemical, mineralogical, isotopic and infrared properties of IDPs?
3. How do IDPs compare with other extraterrestrial materials, specifically unequilibrated meteorites and comet dust?
4. Do IDPs consist of primitive and/or primordial matter?
5. Is there any relationship between IDPs and interstellar matter?
6. Can the study of IDPs contribute to the understanding of basic astrophysical problems? e.g.: the conditions under which solids form in space?

Some of these questions have clear answers, others not. Nor, are the questions independent of each other.

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*In fact, there is currently a spacecraft that has been in near-earth orbit since April of 1984 (the Long Duration Exposure Facility - LDEF I), which has several dust collection experiments on board. Originally scheduled to return to earth in March of 1985, the recovery has now been delayed. Just in the last few weeks, portions of a thermal blanket returned by astronauts from the Solar Max Repair Mission have been found to contain impacts of likely extraterrestrial origin [6b]. This impact debris material will shortly be made available for general scientific study [7].

II. IS IT CERTAIN THAT CHONDRITIC STRATOSPHERIC DUST PARTICLES ARE EXTRATERRESTRIAL?

Yes. However, many early studies of purported interplanetary dust particles were erroneous, and it is useful to review the evidence bearing on this fundamental point.*

The simplest proof that IDPs are extraterrestrial is the recent observation of large densities of fossil nuclear particle tracks in silicate crystals contained within IDPs [12]. Massive nuclear particles ($Z \geq 20$) are needed to produce tracks in silicates. In the terrestrial environment the only natural source of such nuclear particles is the spontaneous fission of ^{238}U, and even in old terrestrial samples, fission track densities are low in silicates. In contrast, samples of extraterrestrial silicates, such as lunar soil grains, typically show high track densities produced by energetic heavy nuclei from the sun and by galactic cosmic rays [a complete discussion of fossil nuclear tracks is given in Reference 13].

The extraterrestrial origin of IDPs had been firmly established even before the recent track observations. Ion probe measurements demonstrated that some IDPs are highly enriched in deuterium relative to hydrogen compared to terrestrial samples [14a]. Still earlier measurements [15,16] showed that the particles possessed nonterrestrial abundances and compositions of noble gases. The fact that IDPs are chondritic in composition is strong evidence in itself of an extraterrestrial origin.

Although the presence of tracks or a large D/H anomaly can be considered as proof that a particular dust particle has resided in interplanetary space, the absence of these effects does not preclude an extraterrestrial origin. It is thus impossible to be certain that all particles labelled IDPs are micrometeorites; however, this is a plausible working hypothesis.

* An excellent description of the early confused state-of-affairs is given by Hodge in his recent book [1]. At one point, there was general agreement between a priori estimates of interplanetary dust influx, particle collections performed with high altitude balloons, and data from electronic detectors in space. Unfortunately, these were all in error by a very large factor. Interplanetary dust collection proved a more formidable problem than early investigators realized.

III. WHAT ARE THE PHYSICAL, MINERALOGICAL, ISOTOPIC AND INFRARED PROPERTIES OF IDPs?

IDPs are an extremely diverse set of objects. It is beyond the scope of this paper to describe all the observations that have been made. The general kinds of measurements that are possible will be briefly described and some particular features will be highlighted.

In spite of their small masses ($\sim 10^{-8}$ to 10^{-10} gms) it has proven possible to develop a variety of techniques for studying individual particles. Initial examination in a scanning electron microscope (SEM) equipped with an X-ray detection system (EDX) reveals the morphologies and major element compositions. Particles can then be individually weighed and their densities determined, although this has been done in only a few cases [17]. More typically, a particle is crushed or otherwise dispersed and parts of it are transferred to an electron microscope grid where detailed measurements of structures and mineralogies can be made by transmission electron microscopy (TEM)[18a-q]. The bulk of the crushed particle can be transferred to a KBr crystal for measurement of its infrared transmission spectrum [19]. If the particle is subsequently mounted on a gold substrate isotopic measurements on different parts of a particle are possible using an ion probe [14a-d]. Alternatively, the particle can be totally consumed in a thermal ionization source mass spectrometer to obtain precision isotopic measurements of several selected elements, or an ensemble of particles can be vaporized in a noble gas mass spectrometer to obtain elemental and isotopic information on noble gases [15,16]. Micro-Raman techniques have been used to establish the presence of "disordered graphite" in at least one particle [34] and Auger spectroscopy has been used on two non-chondritic stratospheric dust particles to look for evidence of surface contamination due to interaction with atmospheric aerosols [35].

Most measurements have been reported by groups specializing in one kind of instrumentation or another, and in only a few cases have the same particles been studied by a variety of techniques. Increasingly, however, sequential or parallel measurements of different types are being made on single particles.

Many IDPs consist of extremely porous aggregates with a typical "cluster of grapes" morphology [9]. Indeed, the <u>erroneous</u> belief has arisen that all IDPs consist of low density, fluffy materials. This is not true. Although all IDPs consist of aggregates of material in the sense that they are not fragments of an igneous rock or pieces of a melt droplet, many are quite compact and have densities of ~ 2 gms/cm^3 or higher [17].

Detailed measurements of the mineralogies and structures of about two dozen particles have been reported [18a-q]. Some particles consist of collections of small anhydrous crystalline grains which are imbedded in an amorphous carbonaceous material. The proportion of amorphous material is highly variable from one particle to the next. The minerals olivine and pyroxene are common, as are magnetite and sulfides of different types. The proportions of different mineral phases vary from particle to particle as do the morphologies and compositions of a given mineral type. Microchondrules, flattened where they are in contact with one another, have been observed, as have lath-like whiskers of pyroxene. Still another large class of particles contain phyllosilicates and give evidence of interaction with water.

A first order result of these studies is that different particles have qualitatively different assemblages of minerals. IDPs cannot be lumped together as a single class of objects; they must be studied individually.

Although infrared transmission measurements were undertaken to provide data that could be compared with astronomical observations, they have also provided a relatively quick means of measuring the dominant silicate mineralogy of whole IDPs. Most IDPs fall into one of three

IR spectral classes called "olivine," "pyroxene," or "layer lattice silicate" from the similarity of the 10 μm features with those of terrestrial mineral standards [19]. Complementary detailed TEM measurements on several particles in the different spectral classes confirm the IR designations. However, the detailed structures seen in the TEM are different for particles in the same spectral class, underlining the importance of treating IDPs as individual objects.

IR spectroscopy can also be used to locate particles with unusual mineralogies. For example, Calrissian, a particle in the layer lattice silicate class, has an atypically strong absorption at 6.8 μm and an accompanying weaker absorption at 11.4 μm. These spectral features were interpreted as evidence for carbonates [19] and subsequent TEM measurements have confirmed the presence of numerous grains of Fe and Mg carbonate [18m].

Ion probe isotopic measurements show large, but variable deuterium enrichments in 5 of 8 IDPs measured to date [14]. Maximum enrichments of $\sim 250\%$ are seen. In particles with deuterium enhancements the D/H values are variable on the scale of a few microns. Correlation of the isotopic signatures with other ion signals indicate that the deuterium excess is associated with C but not with OH [14b]. In contrast, carbon isotopic ratios are found to be constant from one part of a particle to the next although differences between particles are found [14c]. Both Mg and Si give constant isotopic ratios consistent with terrestrial values in three particles [14c]. Earlier, higher precision measurements on several IDPs made using a thermal ionization source mass spectrometer indicated the possible presence of Mg isotopic anomalies at the level of up to 0.4% [20].

IV. HOW DO IDPs COMPARE WITH METEORITES AND COMETS?

Similar in some ways, apparently different in others. Consider first the comparison of IDPs with the fine-grained matrix material of unequilibrated meteorites. The question that dominated the original studies of IDPs was whether they were simply smaller versions of the larger, better known carbonaceous meteorites. No fragments resembling the porous, fluffy IDPs have yet been found in meteorites. It quickly became evident that IDPs were a unique form of extraterrestrial material, different from carbonaceous chondrites and deserving of detailed study in their own right. Moreover, there are distinctive differences in the detailed mineralogies seen in both porous and compact IDPs and the mineralogies observed in meteorites. For example, although CM carbonaceous chondrites and one IR class of IDPs have similar IR spectra dominated by phyllosilicates, the detailed structures of the phyllosilicates are different [18h].

Given the initial question, most authors have emphasized the differences between IDPs and meteorites. Yet there are strong similarities e.g.: the deuterium enrichments seen in IDPs, acid residues of carbonaceous meteorites, and matrix materials from some unequilibrated chondrites. It is not clear whether the differences between IDPs and meteorites are fundamental or whether they represent differences in degree, rather than in kind. It must be remembered that meteorites represent a subset of objects that survive atmospheric entry. There may be large objects, consisting of assemblages of material similar to IDPs, that never reach earth because of their fragility.

At this point it would appear prudent to reserve judgement on the relationship between IDPs and meteorites and treat them as related parts of the same larger puzzle.

Whether true or not, there is a widely held belief, based largely on mass balance arguments, that interplanetary dust is composed primarily of comet dust [23]. It is also believed by many that comets consist largely of primordial material. Direct comparison of IDPs with cometary material suffers from the obvious problem that no one has yet mounted a space mission to return a comet sample.

In the absence of a returned comet sample, the only direct comparison between IDPs and comet dust is based on their optical properties [19]. The best astronomical observations in the infrared are those for Comet Kohoutek where the spectral emission properties of the dust have been obtained from deconvolution of the observational data using an assumed black body spectrum [36]. Comparison with the spectral transmission data for IDPs shows that none of the spectral classes of the particles gives a good match to the comet result. However, a composite spectrum consisting of equal contributions from the pyroxene and layer-lattice silicate classes gives a reasonable match. The olivine spectral class gives the worst fit and it appears unlikely that many particles in this class (some of which are known to be extraterrestrial) are present in Comet Kohoutek.

The present results therefore suggest either that the olivine component of interplanetary dust is not derived from comets or that Comet Kohoutek is not representative of all comets. The olivine class of particles may also be over represented in the limited population of particles (a total of 26) so far measured. These possibilities are obviously not mutually exclusive.

Spectral matching is not a very satisfactory way to approach the question of the relationship between IDPs and comets since even a perfect spectral match would not guarantee that IDPs came from comets. The main thing in its favor is that it is currently the <u>only</u> way to attack the problem.

Apart from obtaining additional, sorely needed spectral data on both comet dust and IDPs, there are several experimental approaches to solving the IDP-comet comparison problem. It has

long been known that most meteor showers have orbits that link them directly with specific comets. Collection and analysis of material from a meteor shower would be a major accomplishment, and a joint Franco-Soviet space experiment which will attempt to collect impact debris from particles associated with the comet Giacobini-Zinner is currently in progress [24].

As discussed more fully elsewhere [25], another important approach would be to construct a space instrument that would measure the orbital parameters of individual particles whose impact debris atoms would be analyzed upon return to the laboratory. Interstellar grains traversing the solar system conceivably could also be located and measured with such an instrument.

Comet rendezvous missions performing sophisticated in situ measurements on dust grains would also help settle the question. And, of course, a sample return mission to a comet would be invaluable.

Scientific interest in IDPs would likely be enhanced if comet samples proved to contain particles of a similar nature. At best, space missions can sample only a few comets in the foreseeable future. If IDPs do indeed come predominantly from comets they are samples of many different objects; further, their heterogeneity shows that they contain a record of a variety of processes.

V. DO IDPs CONSIST OF PRIMITIVE AND/OR PRIMORDIAL MATTER?

Yes and maybe. No generally accepted criteria exist to classify material as either primitive or primordial. For the purposes of this paper, primitive matter is defined as material which has isotopic structures different from those in "average solar system material" and of a nature that cannot be explained by known processes such as spallation reactions by cosmic rays during exposure in interplanetary space. The implication is that primitive materials can be used to obtain information about conditions in the early solar system.

Primordial matter can be defined as (more or less) unaltered material that existed in the (presumed) gas-dust cloud that existed the prior to the present solar system i.e.: interstellar dust. Certain authors have interpreted isotopic data as indicating the presence of such material in meteorites [21]. However, the evidence is circumstantial; no one to date has isolated specific meteoritic grains that have been definitively identified as unaltered interstellar material.

One of the most intriguing of the many isotopic anomalies that have been discovered in meteorites in recent years in the case of Ne-E. This component of Ne consists almost exclusively of ^{22}Ne [22]. A plausible explanation of Ne-E is that live ^{22}Na was incorporated into solid grains where it subsequently decayed into ^{22}Ne. Preservation of the isotopic signature would require that the solid carrier phases were never heated to the point where they totally degassed. Thus they might still be present in recognizable form. However, it remains to be proven that this is the case.

Primordial matter may well exist in both meteorites and IDPs. However, it may be more difficult to identify such material in IDPs simply because of their small sizes. More detailed studies using improved analytical techniques and working with larger IDPs (a program to collect larger stratospheric dust particles is currently in progress) will help address this question. Other aspects of the relationship of IDPs to interstellar matter are treated in the next section.

VI. IS THERE ANY RELATIONSHIP BETWEEN IDPs AND INTERSTELLAR MATTER?

Maybe, maybe not. The most plausible place to look for such links is in dense gas-dust clouds containing strong infrared sources that have been interpreted as protostars. A comparison of the IR absorption features of the protostar W33A with the spectrum of a typical IDP of the layer lattice silicate class shows certain common features. Present in both spectra are features at 3μm, 6.8 μm and 10 μm. The dominant 3μm feature in W33A has been attributed to water ice, a constituent that cannot be present in IDPs where the weaker 3μm feature is attributable to water incorporated in a layered silicate structure. The 10 μm feature seen in both spectra is likely due to silicates.

In the IDPs the 6.8 μm feature is certainly primarily due to carbonate minerals, although a smaller contribution from other phases cannot be ruled out at this time. It is an open question whether carbonates are also responsible for the ubiquitous 6.8 μm feature seen in W33A, and other protostellar objects. Such a possibility was originally suggested based on a comparison of the IR spectrum of the meteorite Murchison with protostellar spectra [26]. However, the absence of an expected accompanying carbonate feature at > 25 μm [27] was also noted. In principle, the presence of carbonate minerals in protostellar sources can be settled by additional astronomical measurements.

Another possible connection between IDPs and interstellar cloud material is provided by the deuterium results. Radio observations show that simple molecules such as HCN can be greatly enriched in deuterium in cold interstellar clouds [28a,b]. If interstellar grains are partly composed of complex organic molecules built up from simple molecules by processes such as photolysis [29], it is plausible that the complex molecules would reflect the deuterium enrichments present in the simple precursor molecules. The large deuterium enrichments seen in IDPs (and in certain extracts from unequilibrated meteorites) could be due to such deuterated interstellar material [30].

Although it is useful to consider points of contact between IDPs and interstellar material, it is equally important to consider what has <u>not</u> been observed. The depletions of certain elements (e.g.: Al and Ca) in the interstellar gas phase have led to the view that interstellar grains in clouds should consist in part of refractory cores [31]. No such refractory cores have yet been reported in IDPs, although fassaite, a common constituent of calcium aluminum rich refractory inclusions in meteorites has been recently found in one IDP [18k].

That grains with the properties expected for interstellar material have not yet been reported in IDPs, does not necessarily mean that such material is not present. Perhaps the problem is one of concentration and scale. Most of the astronomical observations relate to particles of $\sim 0.1\mu$m or less. While grains of this size are routinely measured in electron diffraction studies of IDPs, detailed TEM measurements tend to be made on the largest sub-grains, on those which have euhedral external morphologies, and those which, by definition, give the strongest electron diffraction signals. Many sub-grains of the kind inferred from astronomical measurements could be present as constituents of modest crystallinity without having been singled out in the experimental studies done to date.

VII. CAN THE STUDY OF IDPs CONTRIBUTE TO THE UNDERSTANDING OF BASIC ASTROPHYSICAL PROBLEMS?

Probably - especially on the question of the formation of solids in space. Wherever and whenever the various components of IDPs were formed, several lines of evidence indicate that vapor-solid processes were important. Crystal morphologies unlike those found in terrestrial, lunar, or meteoritic rocks are a common feature in IDPs. Specifically, in fluffy, anhydrous particles the mineral pyroxene is observed to occur in the form of whiskers (rods and ribbons) and very thin platelets. The presence of axial screw dislocations and absence of extensive twinning have been used to argue that the crystals were formed by direct vapor phase condensation [18e]. It is interesting that the results of laboratory experiments on crystal growth served to predict the presence of the observed morphologies prior to their observation in nature [32].

Mineralogical and morphological features found in other anhydrous porous aggregates have been interpreted as evidence for the formation of carbon compounds by heterogeneous catalytic reduction of carbon-rich gases [18f, 18g]. Carbonaceous mantles filaments and fine-grained matrix material are found intermixed with Fe-Ni grains and Fe-Ni carbides of several types, notably hexagonal ϵ-carbide. Similar phases are characteristic by-products of the laboratory decomposition of CO by fine metal particles. Such catalytic processes are widely used industrially with an important subset being the Fischer-Tropsch reactions. Based largely on the observed distribution of molecular weights of extracted hydrocarbons, such processes had been previously proposed as a mechanism for the formation of organic compounds in meteorites [33].

Although these results are intriguing, the lack of detailed knowledge of the kinetics of catalytic reactions in plausible astrophysical environments currently limits the constraints that can be put on the physical conditions under which the observed structures were formed.

Although olivine and pyroxene platelets have been more commonly observed in anhydrous particles, they also occur in IDPs of the hydrated silicate type. In one case, a phyllosilicate crystal is observed in intimate association with a pyroxene crystal suggesting that phyllosilicates are produced by aqueous alteration of pyroxenes [18-k]. Whether this was a liquid or vapor reaction is not clear. It has also been suggested that the carbonates observed in layer-lattice silicate IDPs may have been formed by catalytic reaction with silicates and magnetite in a cooling gas [18-m].

The ensemble of these mineralogical studies, coupled with the fact that many of the particles possess anomalous deuterium abundances, suggest that IPDs contain a record of processes going on early in the history of the solar system, or possibly, before.

VIII. CONCLUDING REMARKS

IDPs are a unique form of primitive extraterrestrial material. Their systematic study is less than a decade old. In spite of the formidable experimental problems in working with particles that are too small to be seen with the naked eye, it has proven possible to obtain considerable information concerning their properties and possible origins. Like any new field, there are many unanswered questions. Continued work by a growing number of investigators, using ever more sophisticated analytic techniques, can be expected to give continued progress and almost certainly to produce some surprises.

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PRIMORDIAL MATERIAL IN METEORITES

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Introduction

"Primordial" is a term which we apply here to material that entered the solar system early and became incorporated into a meteorite without totally losing its identity. Identification of such material surviving in meteorites has so far been solely through recognition of anomalous isotopic compositions of generally macroscopic entities (e.g. inclusions) contained within those meteorites. Those entities are inferred to have incorporated some fraction of primordial particles but the particles themselves may well have been altered beyond present recognition. In the majority of cases, the actual primordial particles have not, in fact, been convincingly identified. In some cases the primordial material was a gas which escaped homogenization with protosolar gas and whose isotopic composition was inherited by a surviving solid phase.

The search for primordial material is therefore the search for isotopic anomalies in meteorites. Isotopic anomalies are, by definition, isotopic compositions which differ from the canonical "solar system abundances" in ways which cannot be explained in terms of local (i.e. solar system) processes such as mass-dependent fractionation, cosmic-ray-induced spallation or decay of radionuclides.

A comprehensive account of isotopic anomalies is impractical here, so it is necessary to be selective. A useful approach seems to be to focus on issues which are potentially addressable through the study of such primordial material. Those issues will be illustrated with specific, but not exhaustive, examples.

Note: Many of the extant anomalies were not originally sought as such but emerged in the course of other investigations. Also, in addition to recognizing an anomaly and identifying, where possible, its host phase, it is generally necessary to consider possible perturbation of the record by secondary alteration processes and to assess the possibility of the isotopic effect having been produced by a purely local process.

Carbonaceous Chondrites

Most isotopic anomalies observed so far have been found in meteorites known as carbonaceous chondrites. The chemical compositions of those meteorites are minimally altered away from our best estimate of "solar system elemental abundances" [Anders and Ebihara, 1982]. The idea has therefore developed that many of the lithic constituents of those meteorites are themselves more or less pristine surviving nebular condensates. (The meteoritic record is generally interpreted in terms of an initially hot and vaporized inner solar system which subsequently cooled permitting nucleation and growth of solid particles that eventually accreted into planetesimals, the meteorite parent bodies, currently identifiable as asteroids.) However, for relatively few of the macroscopic constituents of carbonaceous chondrites is identification as a pristine nebular condensate convincing, the evidence seeming in most cases to favor a relatively complex evolution.

Carbonaceous chondrites are, in fact, breccias, i.e. disequilibrium mixtures of lithic, and organic, components which may have experienced a variety of primary and secondary processing, such as aqueous alteration and/or thermal

metamorphism, prior to final compaction in their parent body regoliths [Kerridge and Bunch, 1979; McSween, 1979; Bunch and Chang, 1980]. Coexistence now of two entities in such a meteorite is no guarantee of any common history before final compaction.

Crystallization of several mineral phases in carbonaceous chondrites, including some formed by aqueous alteration, occurred very close to solar system formation at 4.55Gy ago [Gray _et al._, 1973; Tatsumoto _et al._, 1976; Macdougall _et al._, 1984]. Compaction of carbonaceous chondrites into their current configuration apparently took place over an interval from 4.5 to 4.3Gy ago [Macdougall and Kothari, 1976].

We now consider five issues which may be studied _via_ isotopic anomalies in carbonaceous chondrites.

Nebular Inhomogeneity

This issue is addressed using the isotopic composition of oxygen and titanium in certain types of meteorite, their inclusions and minerals. Oxygen data for a suite of calcium-aluminum-rich inclusions (CAIs, described below) from the Allende meteorite are shown in Figure 1 [Clayton _et al._, 1985]. Mass-dependent fractionation, as in most chemical and physical processes, acting on nominally "solar system" oxygen can only generate isotopic compositions which lie along the dashed line with a slope close to 0.52 [Matsuhisa _et al._, 1978]. Therefore, deviation of the CAI data from that line constitutes evidence for isotopic inhomogeneity in the solar system at the time these

meteoritic samples achieved their present composition. Before showing that these data imply existence of at least three isotopically distinct reservoirs of oxygen in the early solar system, two of them gaseous, we must briefly describe the CAIs, in which so many isotopic anomalies have been observed.

Calcium-Aluminum-rich Inclusions

CAIs are light-colored mm- to cm-sized inclusions embedded in the dark, volatile-rich matrix of certain carbonaceous chondrites. They are enriched in elements, such as Ca, Al, Ti and the Rare Earths, which are believed to have behaved as refractory lithophiles in the early solar system [Grossman, 1980]. For several years they were interpreted as some of the earliest material to have condensed during cooling of an initially vaporized solar nebula [e.g. Grossman and Larimer, 1974]. More recent work, however, has indicated greater complexity than an origin by simply equilibrium condensation from a gas of solar composition [e.g. Wark and Lovering, 1982; Stolper, 1982; Meeker et al., 1983; Kornacki and Wood, 1984; Clayton et al., 1985].

The CAI oxygen data define a trend which can only be produced by either non-mass-dependent fractionation (discussed later) or mixing of nucleogenetically distinct reservoirs (the currently preferred interpretation). That mixing is most likely to have been caused by isotope exchange between inclusion material and an external gaseous reservoir characterized by a different isotopic composition. The individual minerals within a CAI frequently exhibit a spread in isotopic values even greater than that of the inclusions themselves, see Figure 2a. Minerals such as melilite, which are known to

exchange oxygen readily with a gas, are found to be ^{16}O-poor relative to those, such as pyroxene or spinel, which are more resistant to exchange. Exchange is therefore inferred to have been between an ^{16}O-rich solid and an ^{16}O-depleted gas, as illustrated in Figure 2b. The locations of the end-members along the trend line are inferred from various lines of evidence [Clayton et al., 1985].

In contrast to oxygen, the major cations, silicon, magnesium and calcium, in CAIs reveal evidence for mass-dependent fractionation [Niederer and Papanastassiou, 1984; Clayton et al., 1985], as illustrated in Figure 3 for Si. The fractionation trends for the different elements do not generally correlate and imply a complex series of evaporation and/or condensation episodes during the evolution of the CAIs. Those episodes must have disturbed the oxygen isotopic composition, and therefore presumably preceded the isotope exchange episode, described above, because oxygen currently shows no evidence for such mass-fractionation. Thus, it seems likely that the prevalent ^{16}O-rich solid, identified above, was produced by exchange with the ambient gas during the evaporation/condensation episodes. At the high temperature implied by the cation fractionation, close approach to the isotopic composition of the gas seems likely so that existence of a gaseous reservoir close to that marked 1 in Figure 2b seems probable [Clayton et al., 1985].

In addition to the two gaseous reservoirs implied by the CAI data, one further reservoir, apparently a solid phase, may be inferred from the oxygen data for chondrules from primitive meteorites. Chondrules are spheroidal particles, generally polymineralic and with diameters usually in the range a

tenth to one mm, which are prevalent in most chondritic meteorites. Their textures reveal that they were at least partially molten and their compositions show that their precursor materials had experienced little, if any, elemental fractionation from solar abundances for the condensible elements. Although the exact heating mechanism is still unclear, it is generally believed that chondrules were made by localized melting of small solid particles, of either nebular or primordial origin, in the early solar system, probably before substantial accretion of planetesimals [King, 1984].

Chondrules from ordinary and carbonaceous (CV) chondrites show different trends on an oxygen three-isotope plot, as illustrated in Figure 4 [Clayton _et al._, 1985]. Both apparently define mixing lines, presumably reflecting greater or lesser degrees of exchange between the molten chondrule and its gaseous environment. For CV chondrules, those whose petrography shows that they were only partially molten are more ^{16}O-rich than those which were completely melted, indicating that initially ^{16}O-rich solids, designated 4' in Figure 2c, were heated while embedded in an ^{16}O-depleted gas, 2 in Figure 2c. Similar arguments for ordinary chondrites suggest that their chondrules were made by heating, in the same gas, solids which were yet more depleted in ^{16}O, 3 in Figure 2c. Chondrules from a third group of meteorites, the enstatite chondrites, also define the same gaseous reservoir [Clayton and Mayeda, 1985]. It seems logical to relate reservoirs 2 and 2' to each other, and to terrestrial oxygen, by mass-dependent fractionation. The precursor material for the CV chondrules, 4' in Figure 2c, can be identified with material lying on the CAI mixing line and does not, therefore, require a third discrete reservoir, but the chondrule trend line for ordinary chondrites requires existence of a

third, solid, reservoir, depleted in ^{16}O relative to the others, 3 in Figure 2c.

In conclusion, the oxygen data seem to require existence of a minimum of one solid and two gaseous reservoirs in the early solar system, Figure 2d. Whether these all coexisted or whether they represent successive additions to the solar neighborhood is not known, nor is the chemical identity of any of the reservoirs.

In addition to interpretation of the oxygen data in terms of discrete nucleogenetic components, it has been suggested that the data may reflect non-mass-dependent isotopic fractionation in the early solar system. Evidence in support of this view has come from experimental studies of ozone synthesis by a spark discharge acting on molecular oxygen [Thiemens and Heidenreich, 1983]. The isotopic compositions of the product ozone and the residual oxygen are shown in Figure 5, and reveal a trend line with a slope of unity, not the mass-dependent slope of 0.52. The reaction pathways involved in ozone production are quite complex and the actual mechanism responsible for the non-linear fractionation is not fully clear. The fractionating step is apparently neither the initial dissociation of the oxygen molecule nor the (partial) decomposition of the product ozone, but probably involves some metastable intermediate species and may be related to the longer lifetime of heteronuclear species relative to the symmetric homonuclear species [Heidenreich and Thiemens, 1985].

Although the experimental observations are certainly real, their relevance to meteoritic data is less clearcut. The existence of a suitably fractionat-

ing environment in the early solar system has not been demonstrated, nor has a mechanism for efficient trapping of the fractionated products. However, it would be premature to rule out such an interpretation.

Anomalous Ti isotopic compositions are ubiquitous among Allende CAIs and also present in some other meteoritic samples. The dominant anomaly is an excess of ^{50}Ti, up to 28 parts in 10^4, but more subtle effects are also apparent, including deficits in ^{47}Ti and, in some chondrules from unequilibrated ordinary chondrites, in ^{50}Ti [Niemeyer and Lugmair, 1984]. At least four isotopic components are needed to account for the Ti data, though the nature of those components in the early solar system cannot yet be specified. Preservation of the anomalous components as a "chemical memory" in presolar grains [Clayton, 1982] seems to be indicated [Niemeyer and Lugmair, 1984].

Nucleosynthetic Time Scales

Isotopic anomalies generated by decay of now-extinct radionuclides can be used both to resolve small time differences between events in the early solar system, and to define the time interval, Δ in Figure 6, between the end of an episode of nucleosynthesis and the formation of solid objects within the solar system itself. We consider here two examples of the latter application.

The first utilizes several very short-lived radionuclides to place limits on when a "last gasp" of intermediate mass nuclides was produced. A lower limit on that Δ may be derived from an apparent lack of ^{41}Ca in the early solar system. A search in K-poor, Ca-rich minerals from apparently ancient

CAIs in Allende revealed a hint of radiogenic $^{41}K^*$, possibly correlated with Ca/K ratio, but it was deemed not statistically significant and is currently interpreted as corresponding to an upper limit on $^{41}K^*/^{40}Ca$ of 8×10^{-9} [Hutcheon et al., 1984]. This would yield a lower limit to Δ of 1.8×10^6 years.

A model-dependent upper limit on Δ may be inferred from evidence for ^{26}Mg excesses apparently derived from decay of ^{26}Al. For many, but not all, CAIs from Allende and similar meteorites, those excesses correlate with Al/Mg ratios to give an apparent $^{26}Al/^{27}Al$ ratio of 5×10^{-5}, see Figure 7 [Wasserburg, 1985]. Some inclusions yield other values for the $^{26}Al/^{27}Al$ ratio, including a few which give a null value, within error. It is not clear whether different values reflect time differences or heterogeneous distribution of ^{26}Al.

If it is assumed that the ^{26}Al was synthesized in a single event close to the birth of the solar system, the 5×10^{-5} value, if characteristic of a significant fraction of solar system material, leads to a probable upper limit for Δ of 3×10^6 years, given a production ratio for $^{26}Al/^{27}Al$ of about 10^{-3}. Support for this assumption has been inferred from the apparent association of two other radionuclides with ^{26}Al in the early solar system [Wasserburg, 1985]. Many iron meteorites, apparently formed in the cores of several small differentiated asteroids, reveal evidence of excesses of $^{107}Ag^*$ which correlate with Pd content, indicating that they were derived from decay of ^{107}Pd [Kelly and Wasserburg, 1978]. A value of 2×10^{-4} for $^{107}PD/^{108}Pd$ is commonly observed. A similar value, from 0.7 to 1.7×10^{-4}, is calculated for

the ratio $^{129}I/^{127}I$ in many meteoritic materials, based on their contents of radiogenic $^{129}Xe^*$ which correlate with I content [e.g. Niemeyer, 1979; Jordan et al., 1980; Hohenberg et al., 1981].

From the similar fractional abundances of these three radionuclides with very different mean lives, it is inferred that their production and injection into the early solar system were closely related, and that they represent a "last gasp" addition amounting to about 0.01% of the mass of the solar system [Wasserburg, 1985]. However, other explanations for the $^{26}Mg^*$ excess have been proposed. One involves a "chemical memory" due to presolar decay of ^{26}Al in Al-rich circum- or interstellar grains which were subsequently incorporated into the meteorites [e.g. Clayton, 1982]. Alternatively, there is evidence [Mahoney et al., 1984] for a significant steady-state level of ^{26}Al in the interstellar medium, apparently nova-produced, which, if incorporated promptly into the protosolar-system, might explain the meteoritic data [Clayton, 1984; 1985].

The second example uses two relatively long-lived extinct actinides to place limits on Δ for the last substantial addition of real r-process material to the early solar system. The lower limit is supplied by the failure, so far, to find evidence for the existence of live ^{247}Cm in meteoritic material. The decay chain of ^{247}Cm passes through ^{235}U, so that the former presence of ^{247}Cm would be manifested by an anomalously high value of $^{235}U/^{238}U$. Despite occasional reports of such ^{235}U excesses, a conservative intepretation of the extant data places an upper limit on $^{247}Cm/^{235}U$ of 4×10^{-3}, corresponding to a lower limit to Δ of about 10^8 years [Chen and Wasserburg, 1981].

The upper limit on Δ comes from abundant evidence for the presence of live ^{244}Pu in the early solar system. Decay of this nuclide produces fission tracks in minerals and also xenon with a characteristic isotopic spectrum. Both phenomena have been observed, either individually or correlated in the same samples, in a wide variety of meteoritic material. Precise calculation of the actual ^{244}Pu abundance at the moment of formation of the solar system is made difficult by the lack of another, extant, Pu isotope and the fact that Pu has been chemically fractionated during formation of most, if not all, of the samples analyzed to date. Nonetheless, there is reason to believe that the ratio $^{244}Pu/^{238}U$ was about 10^{-2} at 4.6 Gy ago. This leads to an upper limit on Δ of about 5×10^8 years and indicates that the final injection of pure r-process material, amounting to a few percent of the ambient medium, took place between 1 and 5×10^8y before solar system formation [Wasserburg, 1985].

Nucleosynthetic Details

Laboratory analysis of a component believed to have a specific nucleosynthetic origin can, through its superior precision, illuminate details of that nucleosynthesis which would not be accessible to either astronomical measurement or astrophysical calculation. Two examples will illustrate this approach.

The first example involves analysis of two petrographically unexceptional but isotopically unusual CAIs, known as EK 1-4-1 and C-1, respectively. Figure 8 shows the isotopic compositions of two Rare Earth elements, neodymium

and samarium, for these inclusions [McCullough and Wasserburg, 1978a,b; Lugmair et al., 1978]. Substantial deviation from normal solar system values is evidenced by EK 1-4-1, with C-1 showing only a monoisotopic excess at ^{144}Sm. By normalizing to the two s-process nuclides ^{148,150}Sm, the EK 1-4-1 data can be seen to consist of enrichment of p-process ^{144}Sm and of a series of r-unshielded nuclides the distribution of which closely matches that of average solar system r-process material, see Figure 9 [Lugmair et al., 1978]. The conclusion is therefore that EK 1-4-1 contains an above-average concentration of canonical r-process nuclides, and that both EK 1-4-1 and C-1 contain a p-process excess. Coincidence of r- and p-process excesses in one inclusion and a sole p-process enrichment in the other shows that the two processes are not necessarily coupled. Note that the physical/chemical form in which the alien material entered the solar system has not been revealed by analyses to date.

The second example involves analysis of constituents of carbonaceous chondrites quite different from the CAIs which have dominated discussion so far. When these meteorites, and also some unequilibrated ordinary chondrites, are largely demineralized by dissolving the bulk of their lithic fabric in HF/HCl, a tiny residue is left which contains a very high proportion of the primordial noble gas inventory of the meteorite. By a variety of procedures, this noble gas population can be separated into a number of isotopically distinct components, some of which are mundane but others of which reveal isotopic compositions which are believed to be of nucleogenetic origin. The main solid species comprising such an acid-resistant residue are organic matter, elemental carbon, spinel and chromite. We consider here a C component, apparently

emanating from a red giant star, which tells us something about nucleosynthesis in at least one star of that type, and in the next section we discuss what that and other components can reveal about condensation processes in various astrophysical environments.

During stepwise release of Xe from an acid-resistant residue from the Murchison carbonaceous chondrite, a very small fraction of gas revealed an isotopic composition quite distinct from any previously found, Figure 10 [Srinivasan and Anders, 1978]. In every detail it matched very closely the composition of Xe calculated to be produced by the s-process in a red giant [Clayton and Ward, 1978]. Its probable host phase appeared to be elemental C with an unusual isotopic composition ($^{12}C/^{13}C = 42$ [Swart et al., 1983]) which was also consistent with origin in a red giant, thus making such an origin seem very likely. The anomalous Xe in this component was accompanied by krypton which was also anomalous, ^{86}Kr being distinctly enriched over the normal solar system value [Matsuda et al., 1980]. This is of interest because the s-process precursor of ^{86}Kr is radioactive ^{85}Kr with a mean life of about 15 years. Persistence of ^{85}Kr to an extent capable of building up ^{86}Kr implies a mean time between successive neutron captures which was of the same order as the mean life, i.e. 5 to 100 years [Matsuda et al., 1980]. Whether or not this is characteristic of red giants in general, it nicely illustrates the kind of information obtainable from laboratory analysis of "astrophysical" material.

Note that in this case, the physical/chemical nature of the host phase is consistent with the putative astrophysical origin, i.e. condensation in the

atmosphere of a red giant, though more elaborate, if less likely, scenarios, could be envisaged.

Condensation in Astrophysical Environments

For only a few anomalies has the actual presolar carrier phase been reliably identified. Note that identification is influenced by such factors as the ability of the grain to survive throughout an arduous existence, and presence of some distinctive feature during microscopic examination of the sample. Note also that the carrier cannot be assumed to be pristine; alteration is possible at any stage, up to and including preparation of the sample for analysis.

Five host phases are listed in Table 1 for three well established anomalous noble gas components. The nature of Xe-s was considered in the previous section. The isotopic spectrum of Xe-HL is shown in Figure 11 [Lewis and Anders, 1983]; note enrichment of both heavy and light isotopes, which have been attributed to r-process and p-process zones, respectively, of a supernova [Manuel et al., 1972; Black, 1975; Ott et al., 1981]. Xe-HL is apparently associated with nitrogen which is highly enriched in ^{14}N [Lewis et al., 1983]. Its host phase is reasonably securely identified as elemental carbon with a grain size in the range 20 to 90 Å [Lewis and Anders, 1983].

The final component, Ne-E, is essentially pure ^{22}Ne, Figure 12, [Eberhardt et al., 1981], probably formed by decay of ^{22}Na with a 2.6 year half-life. A nova source seems likely for the ^{22}Na, consistent with identification of two

of its host phases as C and spinel [Lewis and Anders, 1983]. However, one of the host phases for Ne-E is apatite [Eberhardt et al., 1981], a mineral which is clearly of secondary solar system origin. How, when and where this mineral became associated with Ne-E is unknown.

Another point worth making is that the 2.6 year half-life of ^{22}Na places severe constraints on the time interval between nucleosynthesis and condensation of the solid phases capable of retaining Ne. Such observations will undoubtedly shed much light on condensation processes in stellar envelopes.

Thermal History of Solar Material

Survival of a presolar isotopic anomaly implies that its host was never heated to a sufficiently high temperature to permit isotopic equilibration with its surrounding medium. Because of major difficulties in placing individual meteoritic components at specific times and locations within the early solar system, existing data do not serve as useful constraints on models of the thermal evolution of the solar nebula, so that this exploitation of isotopic anomalies is largely hypothetical at the present time. However, it is useful to make two comments relevant to this topic.

First, there is very little cosmochemical evidence for nebula-wide high temperatures, i.e. those capable of vaporizing lithic material. There are abundant signs of high temperatures, e.g. presence of chondrules and fractionation patterns involving refractory elements, but it is possible, and even likely, that they reflect processing on a local scale. The best evidence for

large-scale vaporization of the protosolar system used to be the observed lack of isotopic anomalies in meteorites but clearly that argument no longer applies, at least strictly. There is evidence that some meteoritic materials formed by condensation from a gas, e.g. Rare Earth Element patterns for some refractory inclusions [Boynton, 1985], which are consistent with production during cooling of a gas of solar composition, but the scale and location of that event are not rigorously constrained.

Secondly, much of the organic material in primitive meteorites is so highly enriched in deuterium that an origin by ion-molecule reactions in interstellar clouds is widely inferred, [Geiss and Reeves, 1981; Kerridge, 1983]. Besides holding the promise of eventually clarifying some details of molecular cloud chemistry, survival of such material implies that it was never heated above about 600K, though uncertainty about when and where this material entered the solar system inhibits use of this conclusion to constrain conditions in the early solar system.

Local Production ?

For most of the anomalies considered so far, a local, solar system origin is inconceivable because of the extreme conditions needed for synthesis, e.g. the high neutron flux needed for the r-process. For three anomalies, however, such an origin has been proposed, though the flux requirements for production of Ne-E in the solar system seem prohibitive and it will not be considered here.

Both the remaining anomalies also require high proton fluxes in the early solar system. Production of ^{26}Al by p,n reactions on ^{26}Mg requires 10^{21} cm^{-2}, while 10^{25} cm^{-2} are needed to generate the ^{16}O excess by destruction of ^{17,18}O through p,α reactions [Lee, 1978]. Note also that the presence of radiogenic ^{26}Mg* from extinct ^{26}Al does not rigorously correlate with enrichment in ^{16}O, though a loose association may exist. In neither case could irradiation of the entire nebular mass have been involved, the most plausible scenario being irradiation of grain or planetesimal surfaces by an early active sun. If, indeed, the ^{26}Al were associated with ^{107}Pd and ^{129}I, as inferred earlier, a local irradiation origin seems precluded [Wasserburg, 1985]. In summary, local production cannot plausibly be responsible for all the currently observed anomalies and, where not immediately implausible, leads to quite contrived conditions. Nonetheless, such scenarios require further study before they can be ruled out.

Epilogue

It must be reemphasized that the work cited above represents only a small fraction of recent studies into isotopic anomalies. The reader's attention is drawn in particular to the substantial body of work on the isotopic systems of Ca [e.g. Lee *et al.*, 1978; Niederer and Papanastassiou, 1984; Jungck *et al.*, 1984] and Ti [e.g. Niederer *et al.*, 1981; Niemeyer and Lugmair, 1984].

Acknowledgements

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Figure Captions

Figure 1. Oxygen isotopic compositions of a suite of calcium-aluminum-rich inclusions from the Allende meteorite. The ordinate shows variations in $^{17}O/^{16}O$ ratios in parts in 10^3 relative to the terrestrial ocean water standard; the abscissa shows variations in $^{18}O/^{16}O$ ratios. The dashed line corresponds to mass-dependent fractionation. The Allende data define a mixing line, apparently produced by isotopic exchange between distinct components, probably of nucleosynthetic origin. From Clayton et al. [1985].

Figure 2. (a) Oxygen isotopic compositions of individual minerals separated from Allende CAIs. Spinel and pyroxene undergo isotopic exchange less readily than melilite, suggesting that their compositions more closely reflect that of the solid which subsequently exchanged with nebular gas to produce the observed mixing line. This exchange is shown schematically in (b), in which composition #1 is that of the solid and #2' that of the gaseous reservoir. (c) Schematic representation of the data in Figure 4. Allende chondrules, initially with compositions close to #4', and ordinary chondrules, at #3, apparently both exchanged with a gaseous reservoir at #2. (d) Summary of minimal population of oxygen isotopic reservoirs in the early solar system, identified so far. An apostrophe denotes a composition readily derivable, either by mixing or fractionation, from established reservoirs.

Figure 3. Silicon isotopic compositions of a suite of Allende CAIs, analogous to Figure 1 for oxygen. Note that the data closely define a line with a slope of 0.5, indicative of mass-dependent fractionation. From Clayton *et al.* [1985].

Figure 4. Oxygen isotope plot, like Figure 1, for individual chondrules separated from Allende and some ordinary chondrites. Note that for Allende, porphyritic chondrules, which were not totally molten, are more ^{16}O-rich than barred chondrules which were completely melted. From Clayton *et al.* [1985].

Figure 5. Oxygen isotopic compositions generated during spark-discharge production of ozone from molecular oxygen. Square symbols represent compositions of ozone samples: round symbols those of residual oxygen. Note that the data fall on a line with a slope of unity, not on the mass-fractionation trend line (dashed). From Thiemens and Heidenreich [1983].

Figure 6. Schematic representation of the time interval between nucleosynthesis of an element and its incorporation into solid objects during solar-system formation. Elements produced by different nucleosynthetic schemes would be characterized by different values of Δ. After Wasserburg [1985].

Figure 7. Magnesium isotopic compositions of individual minerals separated from an Allende CAI, as a function of Al/Mg ratio. The strong positive correlation indicates that the observed ^{26}Mg excesses resulted from decay of extinct ^{26}Al. After Lee *et al.* [1977].

Figure 8. Isotopic compositions of neodymium and samarium in two unusual Allende CAIs, plotted as deviations, in parts in 10^4 relative to terrestrial values. The nucleosynthetic production mechanisms believed to be responsible for each nuclide are identified. After Wasserburg et al. [1979].

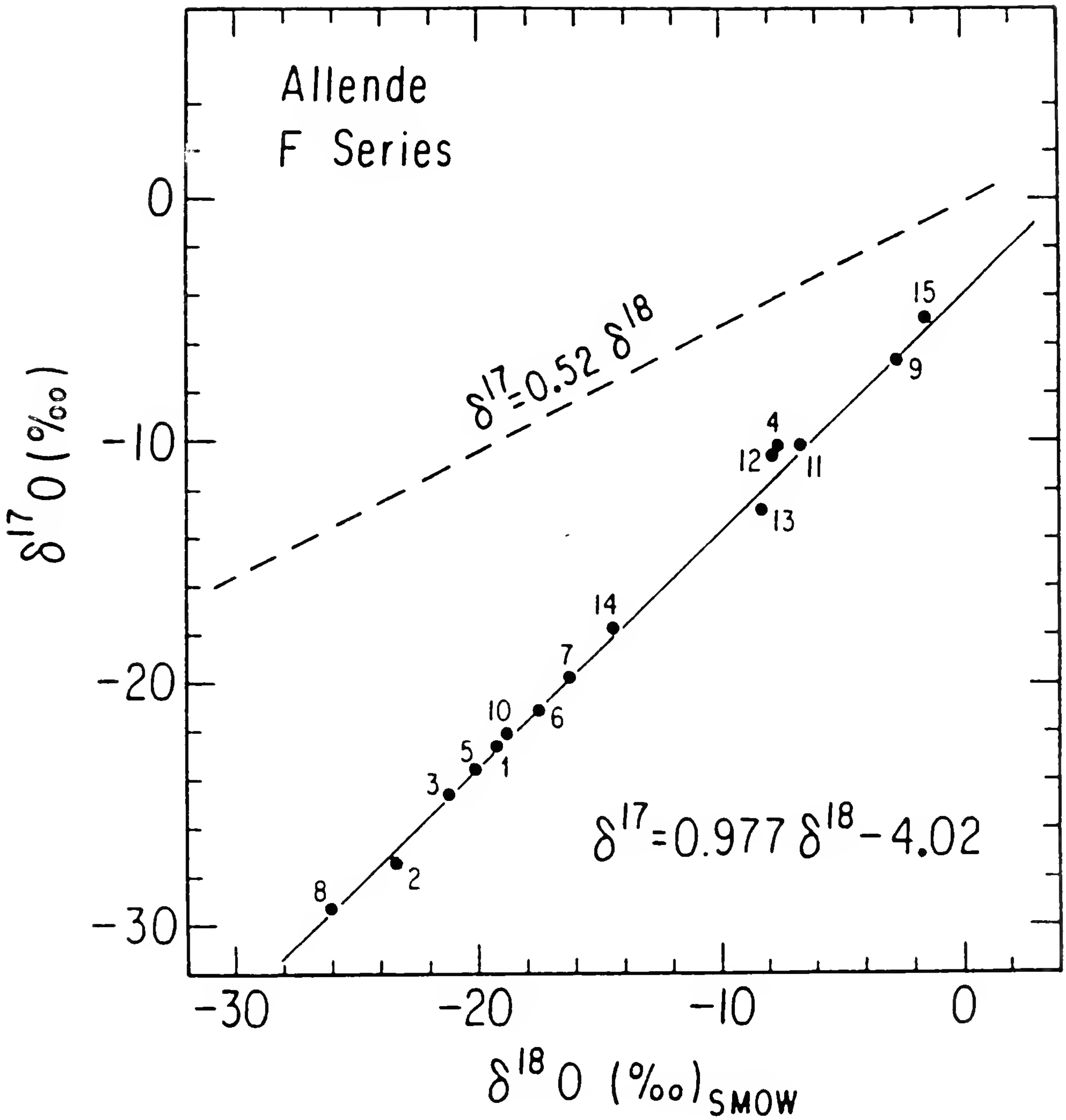
Figure 9. (a) Isotopic excesses in Nd and Sm observed in Allende inclusion EK 1-4-1. Absolute excesses in atoms are plotted versus atomic mass. Note the smooth curves for even- and odd neutron nuclides. (b) Calculated "average solar-system" abundances of the nuclides depicted in (a). Note striking congruency between the curves in (a) and in (b). After Lugmair et al. [1978].

Figure 10. Relative abundances of the xenon isotopes in a small fraction of gas released from the Murchison and Orgueil meteorites. Note the excellent agreement with the xenon composition calculated by Clayton and Ward [1978] to be produced by the s-process in red giants. From Anders [1981].

Figure 11. Isotopic composition of a xenon component extracted from Allende. Note enrichment in both Heavy and Light isotopes relative to "normal" Xe, leading to its designation as Xe-HL. A supernova origin is inferred for this component, see text. From Lewis and Anders [1983].

Figure 12. Isotopic compositions of neon components identified in primitive meteorites. The component known as Ne-E, consisting of essentially pure ^{22}Ne, is dramatically different from the more common components and is believed to be of nova origin. After Eberhardt et al. [1981].

Figure 1



Allende
F Series
$\delta^{17}=0.52\,\delta^{18}$
$\delta^{17}=0.977\,\delta^{18}-4.02$
15
9
4
12
11
13
14
7
10
6
5
1
3
2
8
0
-10
-20
-30
-30
-20
-10
0
$\delta^{17}O$ (‰)
$\delta^{18}O$ (‰)$_{SMOW}$

Figure 2

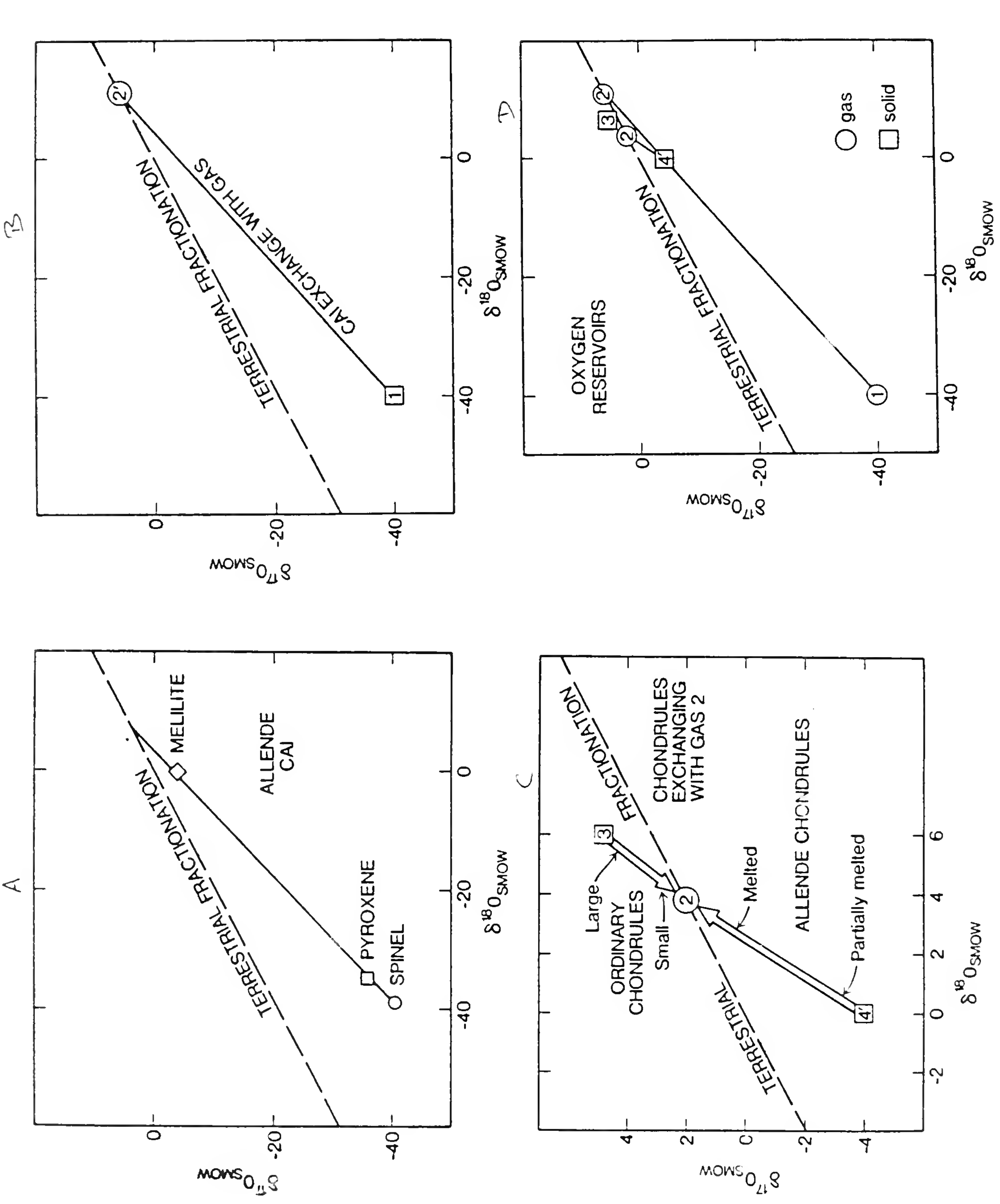

A
TERRESTRIAL FRACTIONATION
MELILITE
ALLENDE CAI
PYROXENE
SPINEL
$\delta^{18}O_{SMOW}$
$\delta^{17}O_{SMOW}$
B
TERRESTRIAL FRACTIONATION
CAI EXCHANGE WITH GAS
$\delta^{18}O_{SMOW}$
$\delta^{17}O_{SMOW}$
C
TERRESTRIAL FRACTIONATION
CHONDRULES EXCHANGING WITH GAS 2
ORDINARY CHONDRULES
Large
Small
Melted
ALLENDE CHONDRULES
Partially melted
$\delta^{18}O_{SMOW}$
$\delta^{17}O_{SMOW}$
D
OXYGEN RESERVOIRS
TERRESTRIAL FRACTIONATION
gas
solid
$\delta^{18}O_{SMOW}$
$\delta^{17}O_{SMOW}$

Figure 3

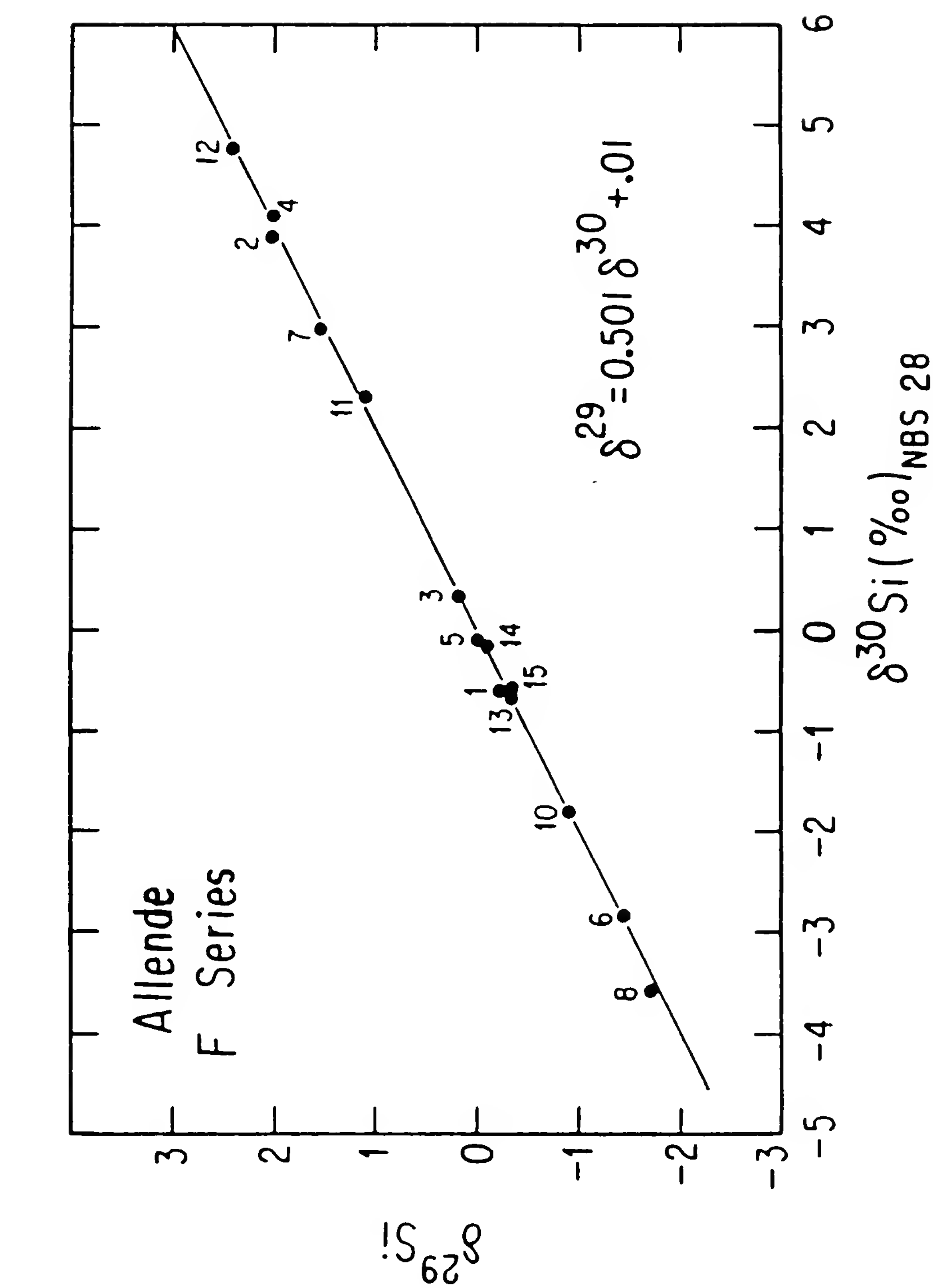
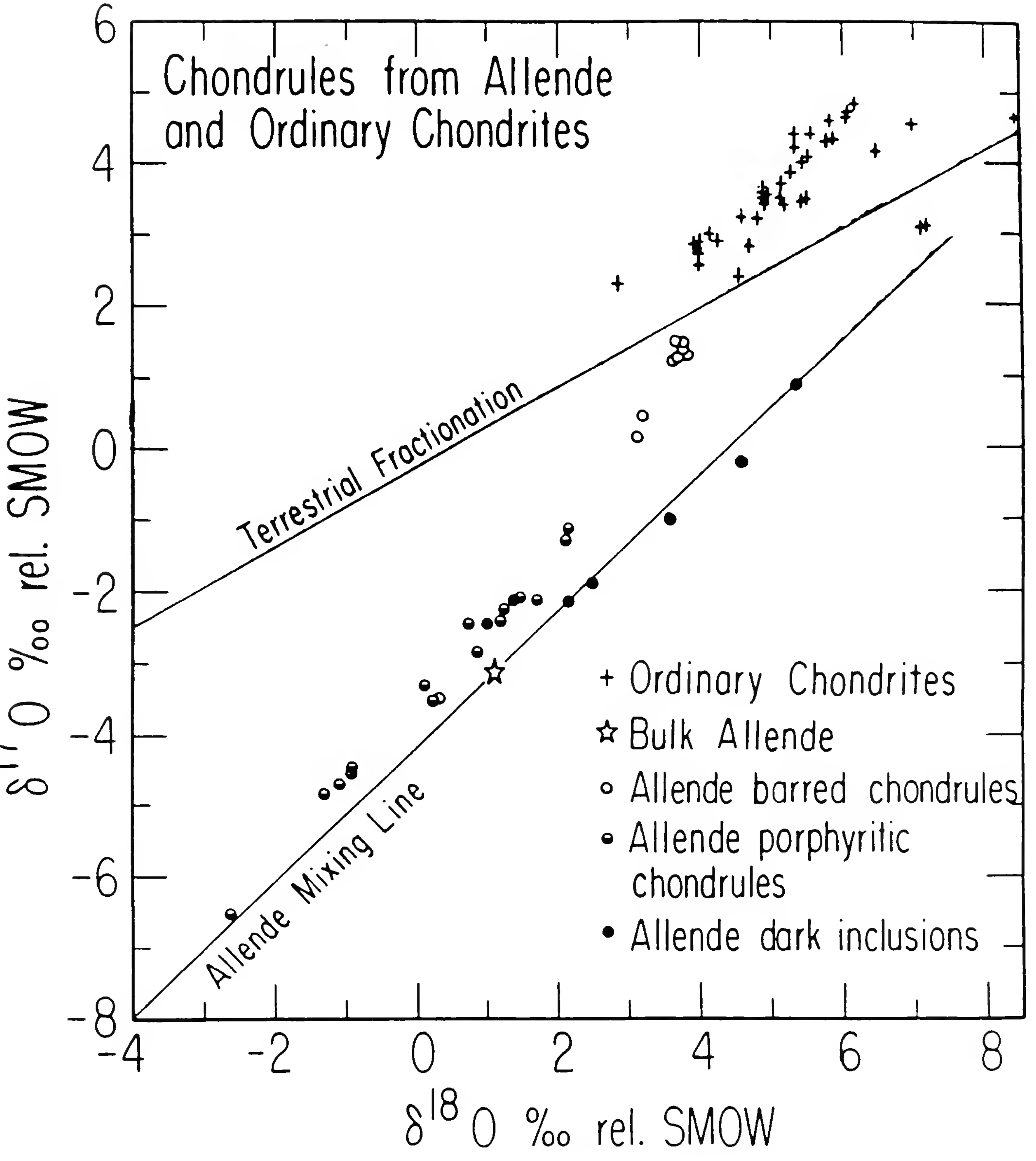

Allende
F Series
$\delta^{29}=0.501\,\delta^{30}+.01$
$\delta^{30}Si\,(‰)_{NBS\ 28}$
$\delta^{29}Si$

Figure 4



Chondrules from Allende
and Ordinary Chondrites
Terrestrial Fractionation
Allende Mixing Line
+ Ordinary Chondrites
☆ Bulk Allende
○ Allende barred chondrules
Allende porphyritic chondrules
● Allende dark inclusions
6
4
2
0
-2
-4
-6
-8
-4
-2
0
2
4
6
8
δ17O ‰ rel. SMOW
δ18O ‰ rel. SMOW

Figure 5

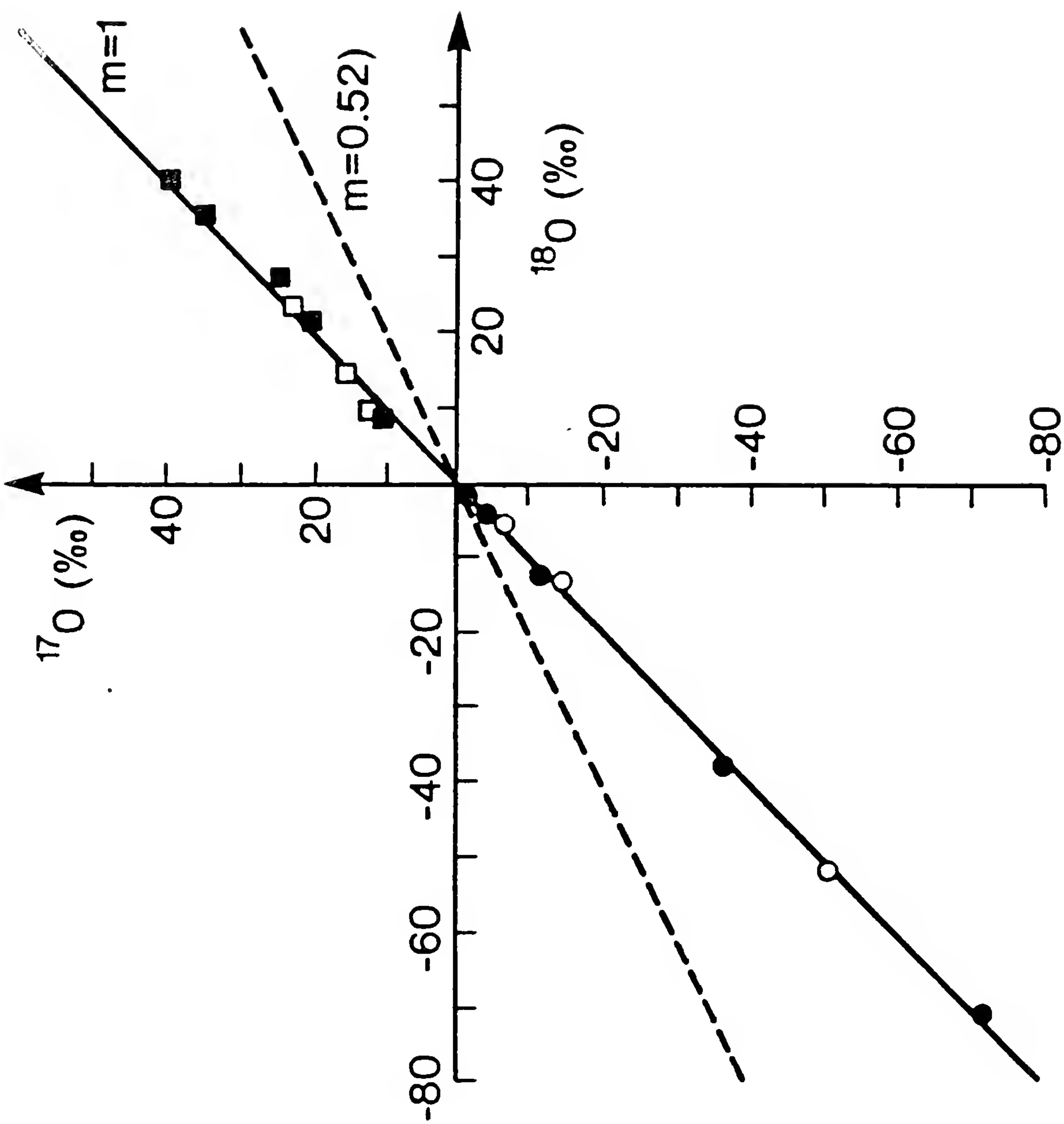
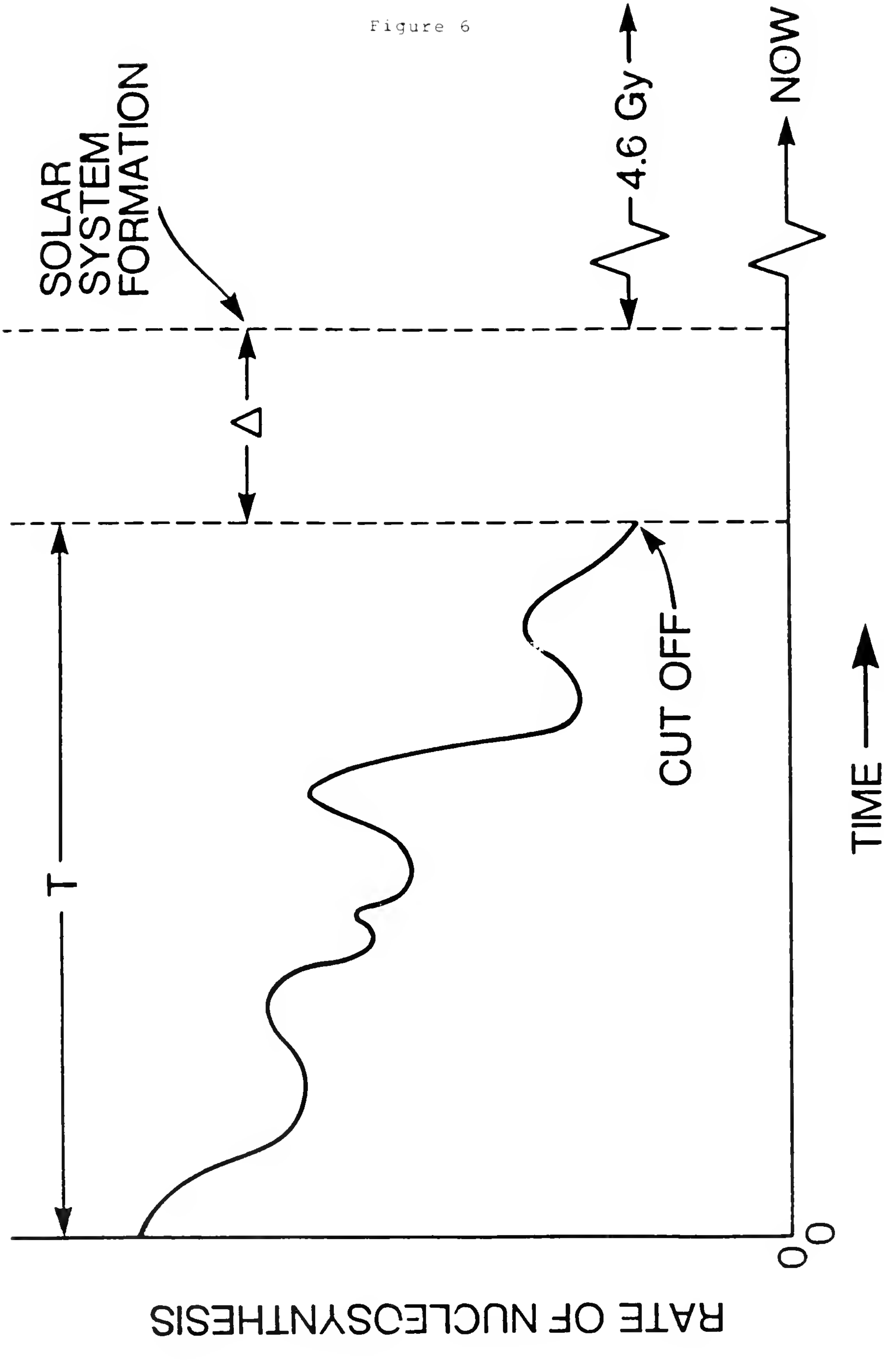
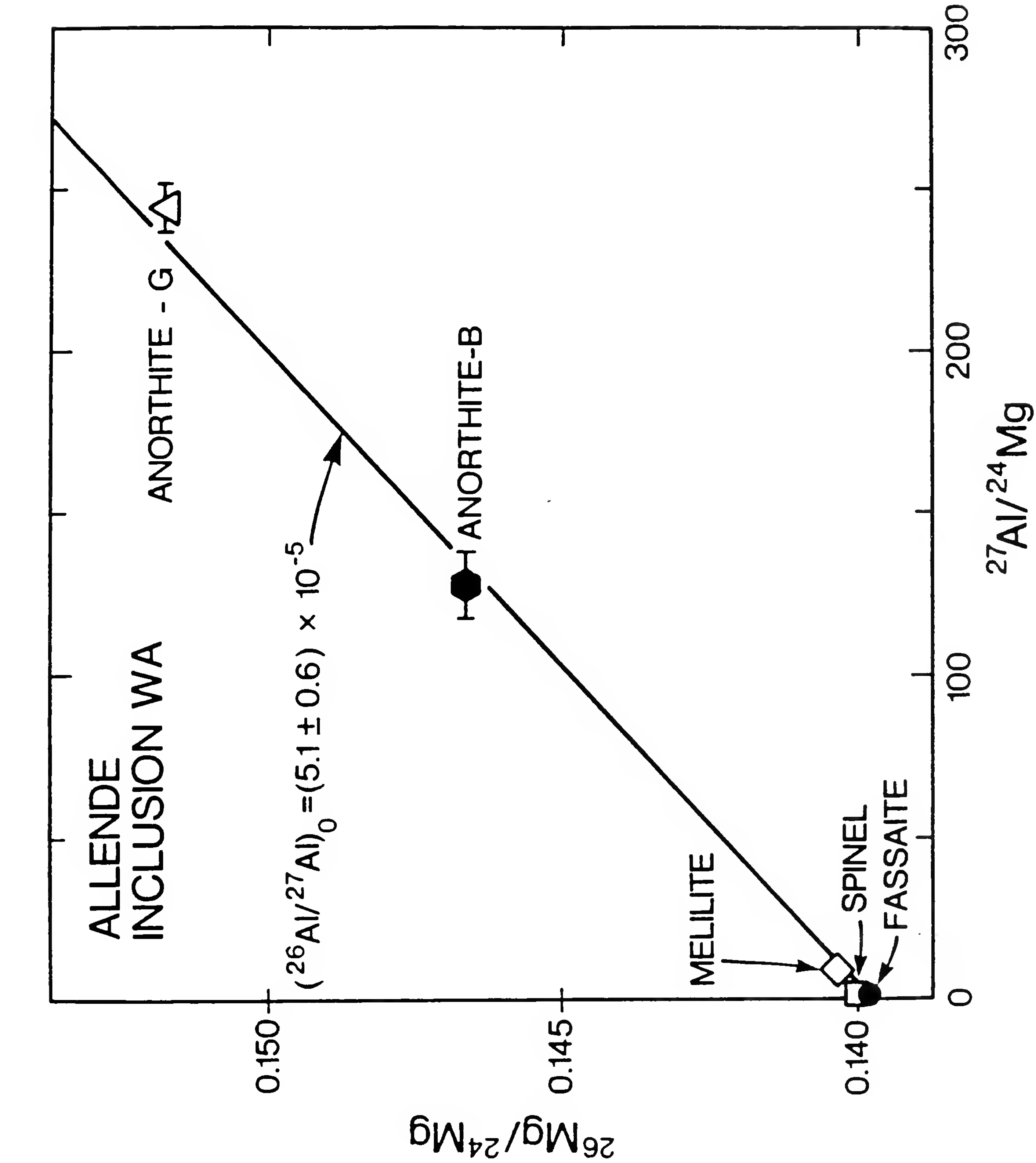


Figure 6



SOLAR SYSTEM FORMATION
4.6 Gy
NOW
Δ
T
CUT OFF
TIME
RATE OF NUCLEOSYNTHESIS
0
0

Figure 7


ALLENDE
INCLUSION WA
$(^{26}Al/^{27}Al)_0 = (5.1 \pm 0.6) \times 10^{-5}$
ANORTHITE - G
ANORTHITE-B
MELILITE
SPINEL
FASSAITE
$^{26}Mg/^{24}Mg$
$^{27}Al/^{24}Mg$
0.150
0.145
0.140
0
100
200
300

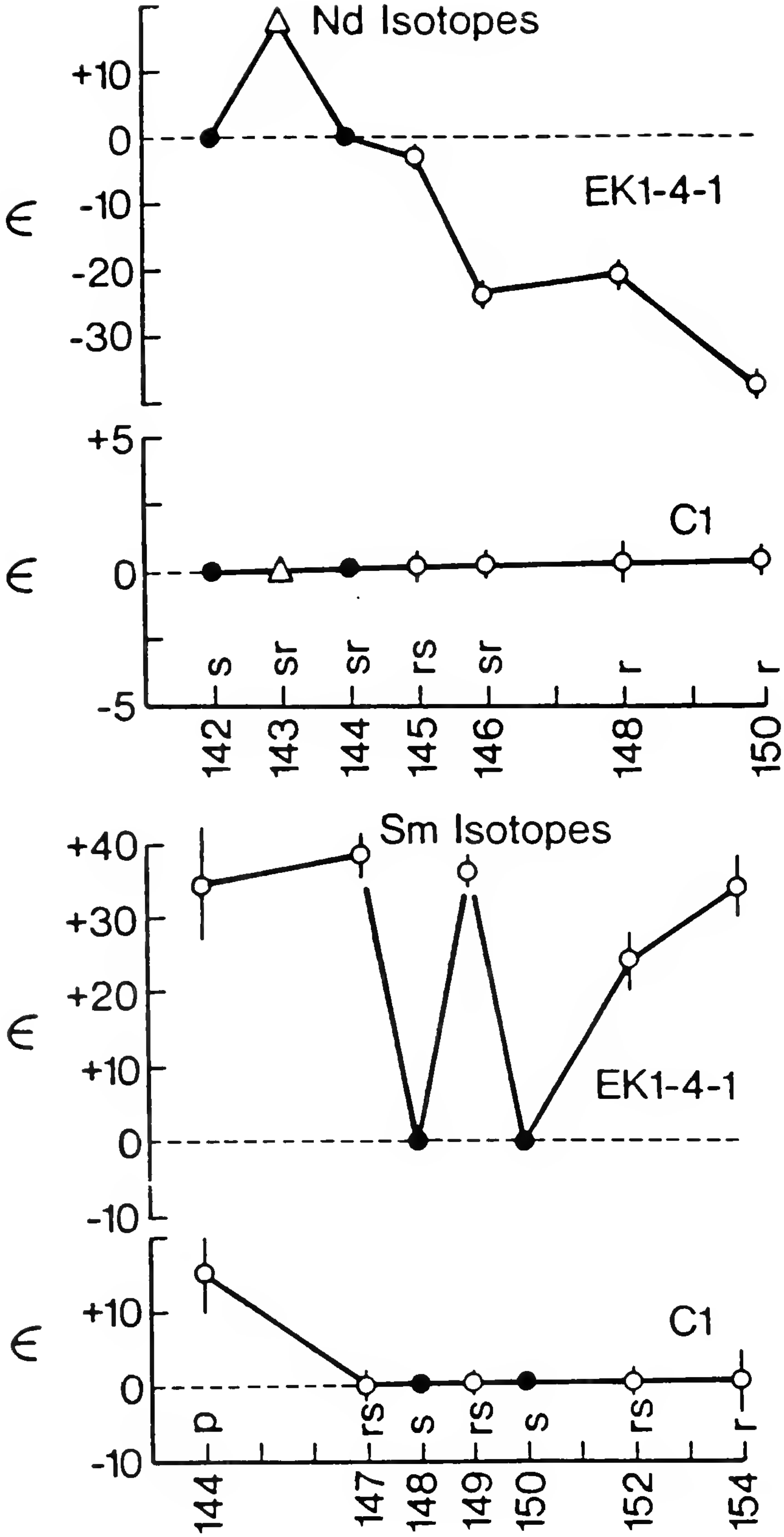
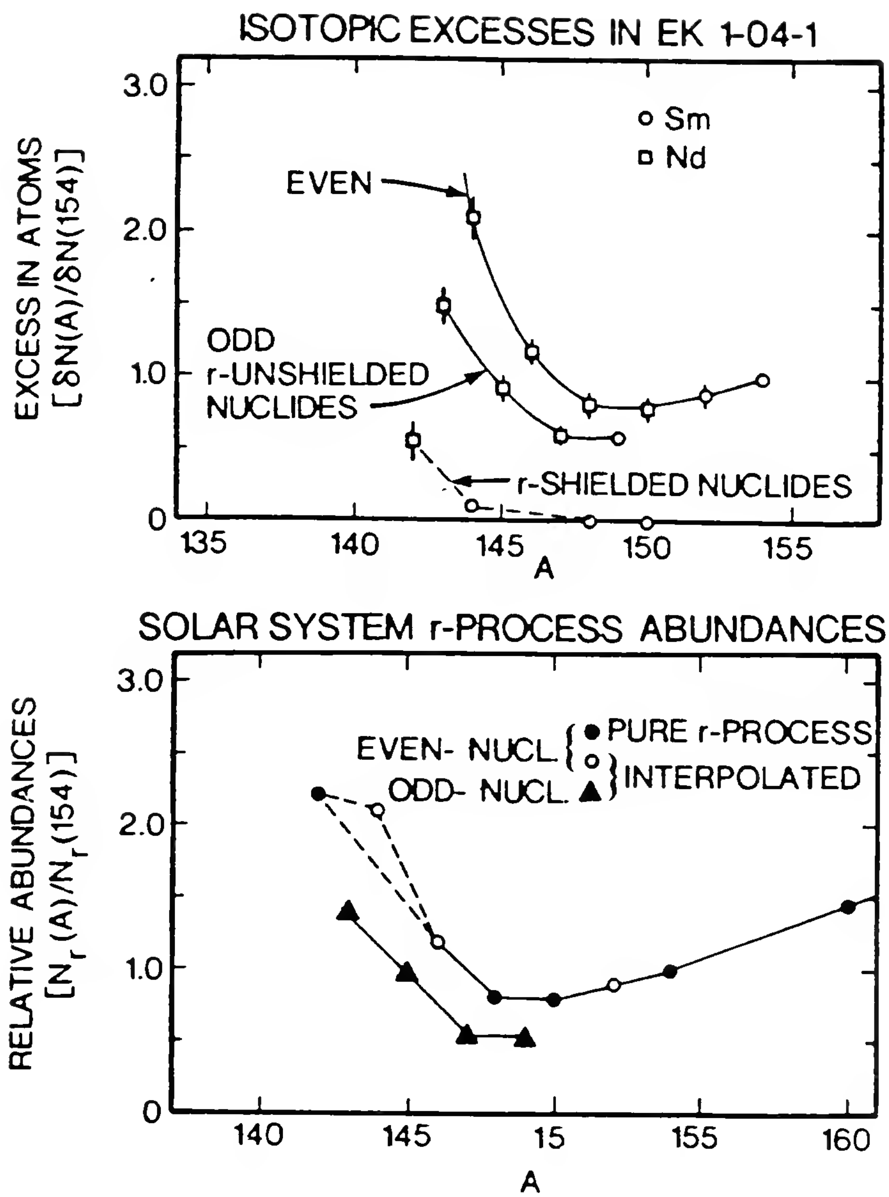
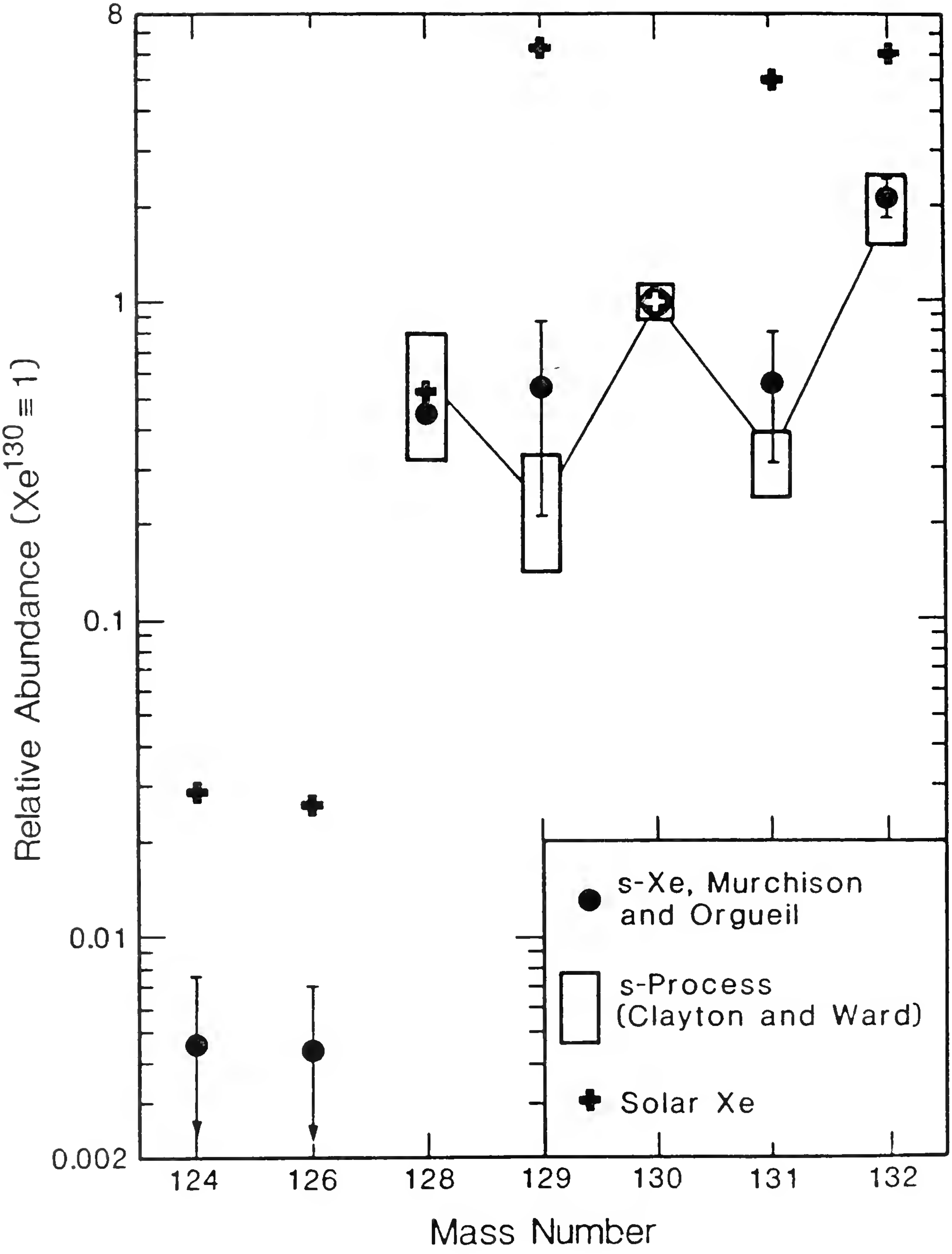

Nd Isotopes
+10
0
-10
-20
-30
ϵ
EK1-4-1
+5
0
-5
ϵ
C1
s
sr
sr
rs
sr
r
r
142
143
144
145
146
148
150
Sm Isotopes
+40
+30
+20
+10
0
-10
ϵ
EK1-4-1
+10
0
-10
ϵ
C1
p
rs
s
rs
s
rs
r
144
147
148
149
150
152
154

Figure 9



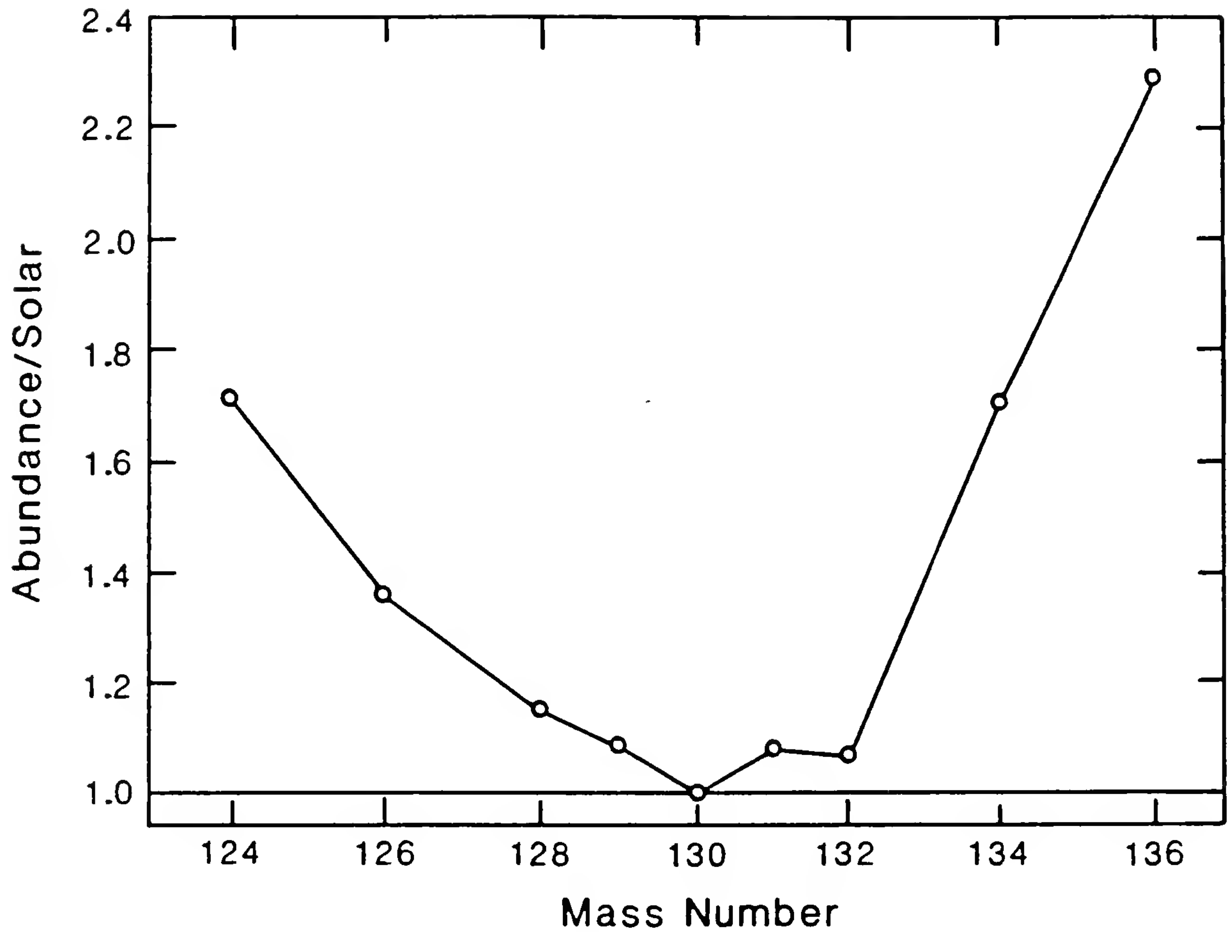
ISOTOPIC EXCESSES IN EK 1-04-1
EXCESS IN ATOMS
[δN(A)/δN(154)]
o Sm
□ Nd
EVEN
ODD
r-UNSHIELDED
NUCLIDES
r-SHIELDED NUCLIDES
3.0
2.0
1.0
0
135
140
145
150
155
A
SOLAR SYSTEM r-PROCESS ABUNDANCES
RELATIVE ABUNDANCES
[N_r (A)/N_r (154)]
EVEN- NUCL.
ODD- NUCL.
PURE r-PROCESS
INTERPOLATED
3.0
2.0
1.0
0
140
145
15
155
160
A

Figure 10



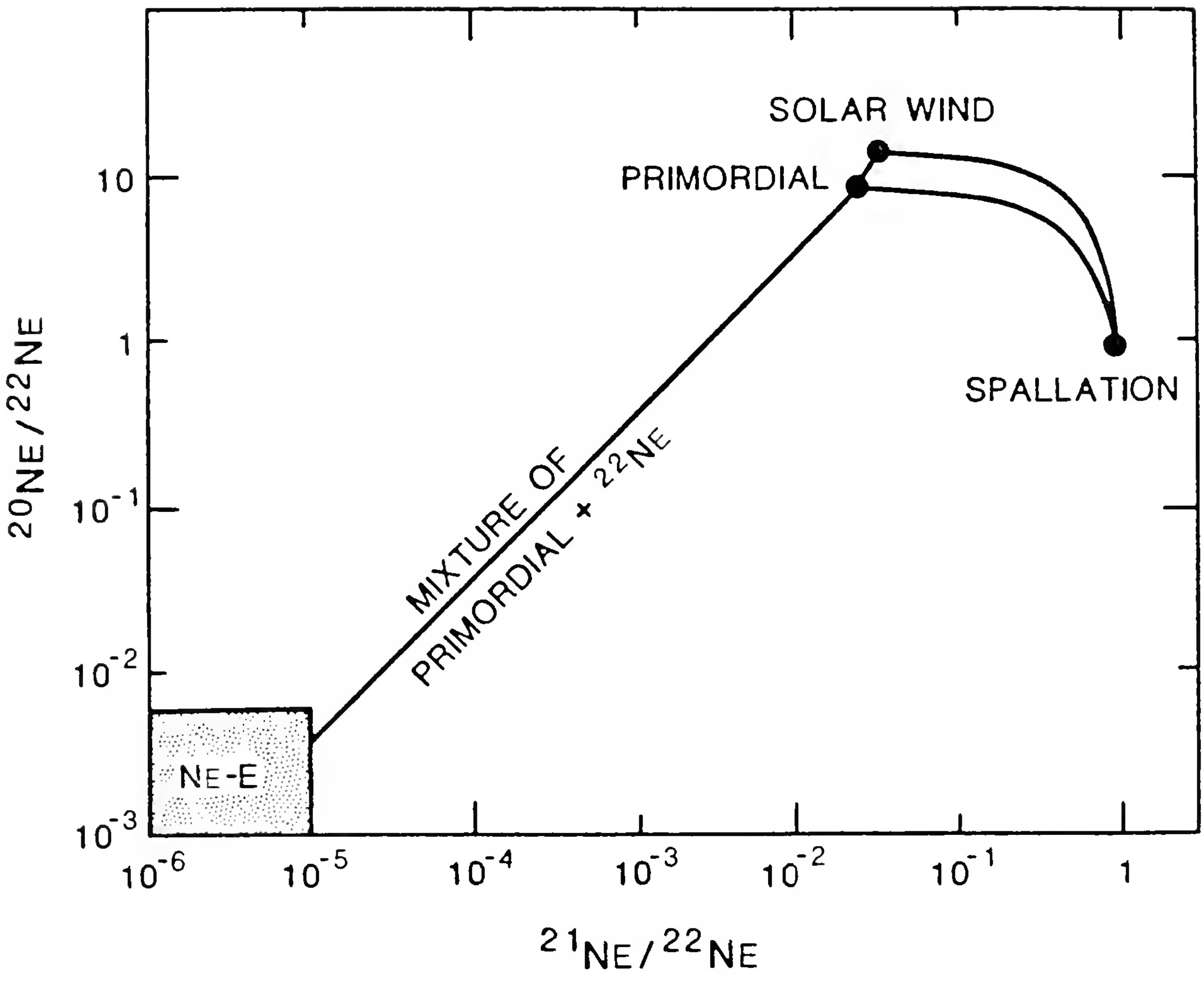
8
1
0.1
0.01
0.002
Relative Abundance ($Xe^{130} \equiv 1$)
124
126
128
129
130
131
132
Mass Number
s-Xe, Murchison and Orgueil
s-Process (Clayton and Ward)
Solar Xe

Figure 11



2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
Abundance/Solar
124
126
128
130
132
134
136
Mass Number

Figure 12


SOLAR WIND
PRIMORDIAL
SPALLATION
MIXTURE OF
PRIMORDIAL + ^{22}NE
NE-E
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
^{20}NE / ^{22}NE
^{21}NE / ^{22}NE

HOST PHASES OF ALIEN NOBLE GASES SUMMARY

Component	Xe-S	Xe-HL	Ne-E(L)	Ne-E(H)	
Material	carbon C	carbon C	carbon C	spinel $MgAl_2O_4$	apatite $Ca_2PO_4(OH,F)$
Release T°C	1400	1000	600	1100	1100
Grain size	0.1-3 μm	∿ 20 Å	1-10 μm		
Source	red giant	supernova	nova	nova	????????????

EXPERIMENTAL INVESTIGATIONS RELATING TO THE PROPERTIES AND FORMATION OF COSMIC GRAINS

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GSFC

I. INTRODUCTION

The interpretation of observations or theoretical analyses of interstellar processes requires a sound knowledge of relevant data. In many instances this can only be obtained by experiments carried out under appropriate conditions. This report is a general survey of the availability of such data applicable to the subjects of this workshop and the techniques for obtaining it. Laboratory investigations of extraterrestrial matter are discussed in the reports by Walker, Kerridge, and Wood.

There exist many significant measurements taken for other purposes but useful for astrophysical problems. It is necessary to use caution and good judgement when treating an astrophysical problem with data obtained for terrestrial purposes. Astrophysical conditions, particularly, temperature, pressure, and surface to volume ratio often differ greatly from those under which the measurements were made. The user needs to be alert to the reliability of the data for the conditions under which it is being used. This constraint often applies when experiments have an astrophysical objective because the experiment may not be possible under actual conditions, for example, at the low densities of interstellar or circumstellar clouds. The next section lists the major collections of experimental data, many of which are well known. Some are more specialized or more recent and not well known.

This report is not intended as a comprehensive review of experimental results or techniques. Its purpose is to serve as a guide to sources of data and call attention to laboratory procedures which have or will supply new, much needed results. New measurements are continuously being carried out and the researcher needs to follow up the literature for such data.

II. SOURCES OF EXPERIMENTAL DATA

1. General

There are a number of comprehensive collections of data covering physics, chemistry, geophysics and other scientific disciplines. These are listed below.

1. Landoldt-Bornstein-Tables of Numerical Values and Functions (in German)
2. International Critical Tables
3. Handbuch der Physik
4. Handbook of Physics and Chemistry - Chem. Rubber Co.
5. Handbook of Geochemistry

There are in addition to these compendia many smaller or more specialized tables of numerical data which are available in libraries. A continuing source of new or improved data is the "Journal of Physical and Chemical Reference Data" available through the American Chemical Society. As with all the above publications, some small fraction of the material is relevant to cosmic dust.

In addition, the series of Annual Reviews e.g. Physical Chemistry, Nuclear Physics, Material Science, will have pertinent articles. Also, to be kept in mind are a growing collection of review publications, e.g. Reviews of Modern Physics, Advances in Physics, Reports on Progress in Physics, Contemporary Physics, Chemical Reviews, Accounts of Chemical Research, Soviet Physicks Uspekhi (Soviet Reviews of Modern Physics), Progress in Surface Science and others. Finally, there are the numerous journals of current research in physics, chemistry and related subjects.

2. Spectroscopy

The standard reference on spectroscopy is Herzberg's very comprehensive four volume treatise "Molecular Structure and Molecular Spectra". Other

sources which supplement that are, Pearse and Gaydon (1965), Suchard (1975, 1976), and Rosen (1970). Ultraviolet spectra of organic molecules are displayed in two multivolume sets, Lang (1961) and U. V. Atlas of Organic Compounds, Plenum Press, N.Y. Clar (1964) presents the near ultraviolet-visible spectra of polynuclear aromatics.

There are a number of collections of infrared spectra of molecules and minerals. For molecules, perhaps the best is the Coblenz Society "Evaluated Infrared Reference Spectra" available from Sadtler Research Laboratories. Inorganic species are treated in "Infrared Spectra of Inorganic Compounds (3800-45 cm^{-1}) R. A. Nyquist and R. O. Kagel and "The Sadtler Infrared Spectra Handbook of Minerals and Clays" edited by J. R. Ferraro. Many texts and reference books on spectroscopy and photochemistry will show spectra and yield other references and as always, journal articles and reviews need to be examined. Fluorescent spectra of a variety of organic molecules and numerous references prior to 1966 may be found in "Fluorescence and Phosphorescence Analysis" edited by D. M. Hercules.

3. Optical Properties of Solids

a. Minerals

The most detailed analyses of interstellar grains have been devoted to the interpretation of interstellar extinction and scattering. This is still an active field of research. The prime requirement is knowledge of the index of refraction of appropriate solids. Some of this data may be found in the works cited in Section 1. Much more extensive data appears in publications concerned with optics of solids. Chapter 10 in "Absorption and Scattering of Light by Small Particles" by C. F. Bohren and D. R. Huffman contains references to several sources. This book is an excellent reference for the entire subject of the interaction of light with small particles. An earlier work by Huffman (1977) emphasizes interstellar grain problems.

In recent years the interest in cosmic grains has resulted in studies of astrophysically interesting solids including measurement of refractive in-

dices. Measurements of the wavelength dependence of the index of refraction, 0.185-2.6 microns, for 24 rocks and minerals are listed and displayed in Chapter V, "Optical Properties of Inhomogeneous Materials", W. G. Egan and T. W. Hilgeman, Academic Press, N.Y., 1979. Optical properties of small metallic colloids, including small size effects, were treated by Hughes and Jain (1979). A number of materials considered as possible grain components have been measured by several investigators. A representative, and not comprehensive list is given in Table 1. Extensive references are given in the above two reports and in the papers cited in Table I.

An important measurement for the study of grains at high temperatures in circumstellar shells or stellar atmospheres is the temperature dependence of the optical properties. Essentially all existing data on optical constants or absorption spectra refer to room temperature. The absorption of a quartz layer heated to temperatures in the range 600-1600 K was measured by Dvurechenskii et al. (1978).

Table I

Measured Optical Properties of Proposed Grain Constituents

Material	Spectral Range	Property	Reference
1. Silicates (lunar rocks)	10-1600 cm^{-1}	Dielectric constants	Perry et al. Moon, 4, 315, 1972
2. MgO (0.1 micron cubes)	400-800 cm^{-1}	Emissivity	JOSA 71, 393, 1981 O. Matamura, M. Cho
3. MgO	IR	Reflectivity, 8K-1960K	J. R. Jaspers et al., Phys. Rev. 146, 526, 1966
4. Silicates	4-14 microns	Emission and absorption spectra	J. R. Stephens, R. W. Russell, Ap. J. 228, 780, 1979
5. Silicates phyllosilicates	7-50 microns	Absorption spectra	A. Zaikowski, et al. "Solid State Ap." ed. (p 151) Wickramasinghe, Morgan, Reidel, 1976

6.	Silicates	1026-1640 A	Complex index of refraction	P. L. Lamy, Icarus 34, 68, 1978
7.	Hydrated silicates, carbonaceous chondrites, amorphous carbonates	2.5-30 microns	Absorption spectra	R. F. Knacke, W. Kratschmer, Astron. Astroph., 92, 281, 1980
8.	Silicates	7-14 microns	Emission spectra	Ap. Sp. Sci. 1979 65, 47
9.	Hydrous Silicates	7-140 microns	Extinction coefficient 2K-1400K	C. Koike, H. Haseqawa, T. Hattori, Ap. Sp. Sci. 88, 89, 1982
10.	Terrestrial Silicates	0.2-50 microns	Complex index of refraction	J. B. Pollack, O. B. Toon, B. Khare, Icarus, 19, 372, 1973
11.	Amorphous Quartz Grains r=200 A	1400-400 cm^{-1}	Complex index of refraction	T. R. Steyer, K. L. Day, D. R. Huffman, Appl. Optics, 13, 1589, 1974
12.	Terrestrial and Vapor Condensed Silicates	4-14 micron	Absorption and emission spectra	Stephens and Russell (1979)
13.	Silicate Minerals	infrared	Absorption	F. M. Penman (1975)
	Non-silicate Minerals	infrared	Absorption	F. M. Penman (1976)
14.	Quartz	2.5-5.5 micron	Emission spectrum 600K-1600K	Dvurechenskii et al. (1978)
15.	Silicates	2-20 or 8-14 microns	Emission spectra	Rose (1977)

b. Carbon

A number of measurements of the optical constants of graphite from the ultraviolet to the infrared for light incident both perpendicular and parallel

to the basal plane have been carried out. References to these papers and discussions of the results are given by Huffman (1977) and Draine and Lee (1984). Corresponding data for glassy carbon have been presented by Williams and Arakawa (1972) and for amorphous carbon by Duley (1984). There is an apparent discrepancy between Duley's results and the measured extinction by amorphous grains. The calculated extinction by small amorphous particles do not show any broad ultraviolet extinction bumps whereas measured extinction curves by Stephens (1980) for 0.03-0.01 micron particles have a distinct peak between 4 and 4.25 micron^{-1}. Similar results were obtained at Goddard where the peak shifted to shorter wavelengths as the size was reduced.

Amorphous carbon films have also been prepared by a glow discharge technique. Anderson (1977) reports a study of the structure, electrical and optical properties of films condensed from a glow discharge in C_2H_2. Lin and Feldman (1983) with a generally similar procedure observed the C-H stretch at 3.4 microns and the CH_2 bending mode at 6.9 microns. The vibrational spectra of hydrogenated, amorphous Si-C films was investigated by Wieder et al. (1979). The effect of possible hydrogen contamination on some of the properties in Anderson's films may be significant. Similar experiments were carried out by Watanabe et al. (1982). The hydrogen concentration is very dependent on deposition temperature.

There have been several experimental studies of extinction by small carbon grains and silicon carbide grains. These are listed in Table II. A later attempt by Hecht and Donn to extend the measurements reported in item 3 was not successful. The very small size grains could not be obtained. However, a regular structure in the extinction curve, generally similar to that reported for the smaller size distribution in the early experiments, regularly appeared. It is believed that the structure is an artifact of the experimental arrangement and thus raises serious questions about the reality of the 1978 data. Further work is needed on the extinction of small graphite grains and the transition from graphite to large polynuclear aromatics.

Table II

Extinction by Carbon and Silicon Carbide Grains

Grain Structure	Experiment	Reference
1. Graphite	Polarization by aligned grains	Cayrel and Schatzmon (1954)
2. Amorphous Carbon	Size and shape of condensate from vapor	Lefevre (1967)
3. Graphite	Normalized extinction coeff., 350-650 nm, r<0.2 micron	Donn et al. (1968)
4. Amorphous Carbon	Extinction	Lefevre (1970)
5. Carbon Smoke	30 nm particles, probably mostly amorphous 120-600 nm	Day and Huffman, Nature, Phy. Sci. 243, 54, 1973
6. Amorphous Carbon	Size, structure, formation of vapor condensed particles	Kappler et al. J. App. Phy. 50, 308, 1979
7. Amorphous Carbon	Extinction 210 nm - 340 microns	Koike et al., Ap. Sp. Sci., 67, 495, 1980
8. Amorphous Carbon, SiC, Silicate Smokes	Extinction 130-800 nm, vapor condensed smokes	Stephens (1980)
9. Amorphous Carbon	Extinction 200 nm-40 micron	Borghesi et al., A&A, 142, 225, 1985
10. SiC	Mass abs. coeff., size distribution <1.5 micron	Dorschner et al. (1977) Astron. Nach., 298, 279
11. SiC	Mass abs. coeff., size distribution <4 micron	Friedemann, et al. (1981), Ast. Sp. Sci., 79, 405
12. Fe_3C	Mass abs. coeff.	Nuth et al. (1984) Ap. J., 290, L41

c. Laboratory Synthesized Non-Volatile Material

With a few exceptions, Table I deals with either terrestrial, lunar or meteoritic material. The exceptions are condensates from laser or arc vaporized material in items 4 and 15 respectively.

Measurements of the optical properties of laboratory synthesized material including small grains have also been carried out. Day (1974, 1976) prepared amorphous magnesium silicates by precipitation from solution and measured their infrared spectrum. Later, he produced amorphous films of magnesium and iron silicates (Day, 1979, 1981) by sputtering a mixed MgSi, Mg_2Si, FeSi or Fe_2Si target in an argon-oxygen atmosphere. The complex refractive indices were determined by dispersion analysis of the transmission measurements.

Amorphous silicate grains have also been obtained by condensation from a mixed vapor. In addition to condensing SiO and Mg+SiO to yield amorphous grains (Day and Donn, 1978a, b; Nuth and Donn, 1982, 1983) these experimenters also investigated changes in spectra and structure when grains were annealed for various time-temperature combinations (Nuth and Donn, 1983a, 1984). More recently experiments have been started at Goddard on the hydration of amorphous grains (Nuth et al., 1985).

Kratschmer and Huffman (1979) irradiated olivine with energetic protons to obtain a crystal with a high density of defects which would thus simulate an amorphous silicate. The infrared spectrum was similar to that of condensed amorphous silicates with structureless 9.7 and 18 micron interstellar features.

The possible role of carbon grains as sources of interstellar extinction started with the proposals by Loretta (1934) and O'Keefe (1939) that the irregular obscuration of RCr B stars was caused by condensation of a cloud of carbon. Caryel and Schatzman (1954) later suggested interstellar polarization could result from aligned graphite grains and measured the polarization of magnetically aligned grains. In 1962, Hoyle and Wickramasinge, carried the

investigation further with the analysis of graphite formation in red giant stars.

These proposals were soon followed by the discovery of the 217.5 nm ultraviolet extinction feature Stecher (1965) and its interpretation in terms of graphite grains by Stecher and Donn (1965).

A variation of the graphite model was introduced with the proposal (Donn, 1968) that an array of polycyclic hydrocarbon molecules (Donn and Krishna Swamy, 1969) could act as Platt particles (Platt, 1956) and may account for the extinction. A preliminary account of experiments on the vapor phase absorption spectra as well as the thermal and photodissociation of polycyclic aromatic hydrocarbons was given by Stief et al. (1970).

A number of difficulties with graphite as the source of the extinction were subsequently noted. Grain optics places a severe constraint on shape and size to account for the 217.5 nm feature (see Gilra (1972) and Hecht (1981) for a more complete analysis). Problems with the formation of crystalline graphite in the interstellar medium including the relevant properties of graphite are reviewed by Czyzak et al. (1982).

Of considerable current interest are the laboratory experiments on the quenched carbonaceous composites (QCC) produced by Sakata et al. (1983, 1984). A film was prepared by allowing the products of a microwave discharge in methane to condense on a quartz or NaCl substrate at room temperature. X-ray diffraction analysis revealed evidence for fine graphitic particles with some hydrogen present. The authors suggest the presence of hydrocarbons with conjugated double bonds. The infrared spectra of the film showed suggestive agreement with a number of observed infrared emission features.

A different explanation for the unidentified infrared emission bands and the long time mysterious diffuse interstellar bands is the proposal that they arise from polycyclic aromatic hydrocarbons (PAH's). The proposed infrared identification was due to Leger and Puget (1984), primarily based on laboratory spectra of coronene, a symmetric seven ring aromatic molecule.

Allamandola et al. (1985) showed that the Raman spectrum from auto exhaust compares well with the spectrum of the Orion bar in the 5-10 micron interval. The laboratory sample was a mixture of non-crystalline graphitic material and PAH's. Experiments on the residue composition from ethylene diffusion flames (Chakraborty and Long, 1968) determined the PAH concentration dependence on the oxygen and hydrogen concentration. Subsequently and simultaneously Leger and d'Hendecourt (1985) and van der Zwet and Allamandola (1985) pointed out that a correlation between visible aromatic spectra and the interstellar bands is to be expected but no identifications of bands were presented. The latter authors report experiments are under way to seek such comparisons.

Beginning about 1970 Sagan and Khare, summarized in their 1979 paper, have produced a variety of complex organic solids from cosmically abundant gases CH_4, C_2H_6, NH_3, H_2CO and H_2S. The products, produced by ultraviolet irradiation or spark discharge, are brown sticky films named tholins. They propose such material as constituents of the primitive oceans, aerosols in atmospheres of the outer planets and as being present in comets, carbonaceous chondrites and the interstellar medium.

Over the last decade or so Hoyle, Wickramasinghe and colleagues have investigated a variety of carbon compounds as the source of the interstellar extinction. Generally, they compared the infrared spectra of the material with the interstellar spectra. In a few cases the ultraviolet-visible spectrum was also determined and compared. This work is reviewed in a recent publications (Hoyle et al., 1985). Yabushita and Wada (1985) describe an attempt to reproduce the measurements on yeast and E. Coli made by Hoyle and colleagues. They found significant discrepancies between the two laboratories but pointed out the problems of exactly reproducing results. Yabushita and Wada emphasized the need to exactly specify the conditions under which the measurements are made. Moore and Donn (1983) also measured the infrared spectrum of E. Coli. In order to avoid the high pressures in preparing a KBr pellet they incorporated the E. Coli in a mull and reproduced the 3.4 micron feature. However, other absorption features, equally strong, at longer wavelengths than measured by Hoyle do not show up in the interstellar extinction.

d. Small Particles

Much of the existing data and many experiments deal with bulk properties and macroscopic material. This workshop is concerned with aggregates of matter below about one micron. Some proposals for grains have been as small as 5 nm where significant deviations from bulk behavior occur (Small Particles, 1977, 1981; Jortner, 1983; Rupin and Engelman, 1970).

There have been many laboratory programs to prepare and study a variety of characteristics of small particles. A number of these are described in the references in the preceding paragraph. Kamijo et al. (1975) present results for a number of refractory elements and oxides using the gas evaporation technique. References are given to other Japanese work in this area. Optical properties were not measured. Tables 1 and 2 include a number of similar experiments where the emphasis was on optical properties of the condensates.

Once particles are prepared the determination of size and composition for multielement grains becomes necessary. The characterization of particles by many different techniques is discussed in a National Bureau of Standards publication (Heinrich, 1980). Methods for the study of surfaces (Kane and Larrabee, 1974) and thin films are quite similar and may also be used. Many results and techniques for thin films can be found in the series "Physics of Thin Films, Advances in Research and Development." The initial stage of laying down a film consists of the formation of isolated aggregates.

4. Thermodynamic Data Including Vapor Pressures

Among the physical and chemical data found in the references in Section II, are extensive sets of thermodynamic properties of a variety of materials. In addition to those collections there are a number devoted to the subject of this section. Vapor pressures as a function of temperature are given by A. N. Nesmeianov (1963) for the elements and Baublik et al. (1984) for a large variety of compounds. The "Handbook of Chemistry and Physics" (Weast, 1985) revised about every year, gives constants for the vapor pressure equation of many compounds. Stull (1947) tabulates temperatures of organic compounds and

inorganic compounds respectively at which the vapor pressure is 1, 5, 10, 30, 40, 60, 100, 200, 400, and 760 torr.

The most comprehensive collection of thermodynamic data appears to be the JANAF Thermochemical Tables (D. R. Stull and H. Prophet, 1971) published and updated by the Office of Standard Reference Data, U.S. National Bureau of Standards. The JANAF Tables give the temperature dependence for: heat capacity, entropy, Gibbs energy function $(F^o-H^o_{298})/T$, $H^o_T-H^o_{298}$, ΔH^o_f, ΔG^o_f, and log Kp. ΔH is the enthalpy, F or G is the Gibbs Free Energy and Kp is the equilibrium constant in units of atmospheres. The vapor pressure P is obtained from the equation:

$$\ln \Delta Fo_{vap} = -RT\ln P$$

Although the JANAF tables list ΔF in the next to last column, for interpolation purposes it is more accurate to use the Gibbs Function, $-(F^o_T-H^o_{298})/T$, which varies much more slowly with T. Then, ΔF_{vap} is given by:

$$F_{vap} = T\ [-(F^o_T-H^o_{298})/T]_{(cond)} - [-(F^o_T-H^o_{298})T + H^o_{f,298}\ (v) - H^o_{f,298}\ (cond)$$

$$\text{and } P_{vap} = \exp\ [-\ F_{(vap)}/RT]$$

where P_{vap} will be in atmospheres. Note that JANAF units are cal/molK for $-(F^o-H^o_{298})/T$ and Kcal/mole for $\Delta H^o_{f,298}$. The gas constant, R = 1.987 cal/mol. K.

The application is very straightforward for monatomic solids, for example, iron. For solids with complex compositions, as are all silicates, vaporization and stability can be discussed according to the treatment of Grossman and Larimer (1974). The reverse process (condensation) is more involved as discussed by Donn (1976, 1978, 1979) and at present no reliable procedure is available (Donn et al., 1981; Donn and Nuth, 1985). Extensive data for vapor pressures at low temperatures are given in the above collections. An additional source is found in Honig and Hook (1960).

III. EXPERIMENTAL INVESTIGATIONS OF GRAINS

1. Optics

In Section 2, data and some measurements on spherical and compact non-spherical particles were presented. This section deals with scattering on well defined, irregularly shaped grains.

One of the earliest studies was by Donn and Powell (1963) also Powell et al. (1967). The Angular scattering for both polarizations at two visible wavelengths were measured for micron size MgO cubes and ZnO fourlings. The latter have four symmetrically arranged narrow prongs extending from a central nucleus in the ideal case (which did not always occur). For the cubes, Mie calculations for a very similar distribution of spheres, gave a good match. However, with the fourlings, more large particles were needed and the measured scattering did not match either the angle or wavelength predictions.

More detailed and systematic investigations of scattering by irregular particles can be performed using microwaves and thereby scaling the particle dimension from microns to centimeters. An extensive program for this purpose was initiated by Greenberg (Wang and Greenberg, 1976; Greenberg and Gustafson, 1981). It was continued at The State University of New York at Albany (Schuerman, 1980a). The laboratory is currently run at the University of Florida, Gainesville. A similar laboratory has been operating at Ruhr University, Bochum, FRG (Zerull, 1980). Additional references to experiments on scattering by irregular particles, both optical and microwave, can be found in "Light Scattering by Irregularly Shaped Particles" (Schuerman, 1980b).

2. Sputtering

Sputtering of atoms or molecules off surfaces of either icy or refractory materials is an important process for grain evolution in a number of astronomical environments (e.g. Barlow; 1978). Experiments on sputtering by energetic ions have been carried out in several laboratories and results applied to astrophysical problems.

In the case of interstellar grains refractory "minerals", polymeric carbonaceous macromolecules and icy surfaces are likely to be involved. For solar system objects including satellites of the outer planets and cometary surfaces, volatile ice mixtures are the major constituents. Zodiacal and interplanetary dust and a large proportion of cometary grains will consist of refractory material. Barlow references sputtering experiments prior to about 1970. The basic techniques employ plasma discharges or ion beams to obtain the impacting ion. The ion beam method permits more quantitive measurements as the energy and angle of impact can be accurately controlled.

Detailed discussions and summaries of experimental results are given by Kaminsky (1965), Behrisch et al., (1973) and particularly Behrisch (1981, 1983). The last reference is a continuing series "Sputtering by Particle Bombardment". Volume I is subtitled "Single Element Compounds". Of considerable relevance is Chapter VII "Alloys and Compounds, Electrons and Neutrons, Surface Tomography". The chapter by Betz and Wehner, "Multicomponent Materials", provides data for a number of species of astrophysical importance. A third volume "Angular, Mass, Energy and Charge Distribution" is in preparation.

Sputtering produces a very complex structure on the irradiated surface. This is shown in the section on surface tomography in Behrisch (1983). The consequences for interstellar grains with regard to continuous exposure leading to destruction and for optical properties may be important. These experiments have been done on well ordered surfaces, the effect on amorphous surfaces and for grains under a micron in diameter need to be studied.

A brief but rather thorough review, with many references, to sputtering effects on condensed volatiles is given by Johnson et al. (1985). An additional very recent reference is the forthcoming proceedings of the NATO Conference on "Ices in the Solar System" edited by J. Klinger.

The active centers doing experiments in this area are at the University of Virginia (R. E. Johnson), Bell Laboratories (L. J. Lanzerotti), and the University of Catania in Italy (V. Pirronello).

3. Nucleation and Condensation

A number of calculations of grain formation in stellar atmospheres and circumstellar shells have been carried out over the past two decades (see Donn and Nuth, 1985 for references). The assumptions used in these investigations have been questioned by Donn in a series of papers, including the reference above. An experimental study of the condensation of refractory materials at temperatures in the range 750-1200K was undertaken at the Goddard Space Flight Center to study this problem (see Donn and Nuth, 1985 for references). In these experiments the reactant or reactants were thermally vaporized to form a cloud at a known temperature within which particles condensed. An inherent difficulty with this technique is the attainment of good mixing in the vapor phase with multi component mixtures. These experiments were an extension of those described in Section IIc for the preparation of synthetic silicate grains. For a variety of other purposes, the problem of the condensation of refractory materials has been investigated at a number of other institutions using different techniques, primarily employing shock tubes. These have all been referenced and very briefly described by Donn and Nuth. In all cases the experiments resulted in significant disagreement with nucleation theory.

At Goddard, plans have been developed for studying both nucleation and particle formation from multicomponent gases in a flow system. The separate components will be mixed in a high temperature furnace where condensation cannot occur. The now well mixed gas will flow into a variable, lower temperature furnace and condense under controlled conditions.

4. Clusters

The proposal that nucleation theory cannot handle mutlicomponent mixtures (Donn, 1976) was based on the formation of metastable clusters that affect the final grain composition. Several of the condensation experiments referenced in the last Section yielded particles with non-equilibrium composition (Nuth and Donn, 1982, 1983; Stephens and Bauer, 1985).

In order to study the condensation process and determine thermodynamic and kinetic data for developing a kinetic theory of condensation an investiga-

tion of the precondensation clusters is an important procedure. In recent years there has been extensive research into the properties of clusters, largely because of their role as catalysts. This work is well presented in several conference proceedings ("Experiments on Clusters", 1984; Gole and Stwalley, 1982; Borel and Buttet, 1981). Gas phase cluster experiments for the most part involved single species, often metallic or in several cases alkali halides. In all instances the cluster formed by expansion and cooling of the carrier gas plus condensible species so that the temperature-pressure conditions of cluster formation were not determined.

In the last two years two procedures with considerable astrophysical significance have been applied to the investigation of clusters. Instead of using an inert ambient carrier, a small concentration of reactant is introduced into the flowing carrier. By this means reactions of cobalt and niobium clusters with hydrogen (Guesir et al., 1985) and iron with molecular hydrogen (Ricktsmeier et al., 1985) were studied. With all three cluster types, the reactivity was a strong function of cluster size. Whetten et al. (1985) reacted iron clusters with O_2, H_2S, and CH_4. In all cases atomic iron is unreactive, the reactivity of iron clusters tends to increase with cluster size and levels off for the larger clusters. CH_4 did not react with iron clusters.

By vaporizing arsenic or cesium with sulfur, Martin (1984a, 1984b) obtained mixed clusters with a wide range of composition ratios. In these experiments the two species were vaporized from adjacent crucibles (Cs + S) or as arsenic sulfide from a single crucible. Reactant gases were also introduced into the helium carrier. Research in the new area of cluster reactivity and composite clusters is very active and new results are continually reported.

An experimental program on clusters aimed at the astrophysical problem of grain formation has been undertaken at Goddard (Donn et al., 1981). The emphasis will be on the formation of silicate grains composed of cosmically abundant metals. The plan is to create and then condense multicomponent vapor mixtures. The composition of the vapor, temperature and pressure of cluster

formation are the basic parameters to be varied in the experiment. The size and compositional distribution as a function of temperature are the results to be measured. This information will be a major contribution to the understanding of cosmic grain formation.

5. Low Temperature Experiments

1. Matrix Isolation

There is always a question of organization in a review covering a broad area of research - How best to present material which overlaps several sections? In the present instance clustering has been studied using high temperature vaporization as in Section III-1 and also in low temperature matrices. The latter aspect is considered here.

There is a rather long history of the study of clustering and reactivity in matrices. The general techniques are reviewed by Moskovits and Ozin (1976) and examples appear in Gole and Stwalley (1982). Primarily spectroscopic applications are given by Meyer (1971). Two reviews emphasizing the study of molecules prepared at high temperatures have been written by Weltner (1967, 1969). He has also studied small carbon clusters in inert matrices (Weltner 1964a, b, 1966, 1976). Kratschmer et al. (1985) deposited carbon vapor at 10K and warmed up the film while monitoring the spectrum. They obtained results which may be compared with several diffuse interstellar bands.

Wdowiak (1980) has condensed the discharge products of methane-argon mixtures at 10K and examined the visible spectrum as a function of time and ultraviolet bleaching. Suggestive similarities with diffuse bands occurred in these experiments also. Khanna et al. (1981) monitored changes in the spectra of SiO in N_2 with warmup. In addition to the growth of small polymers of SiO, they obtained a non-volatile residue that had an absorption similar to that of the Si_2O_3 particles that characterize condensates from SiO vapor. Similar results were obtained for Mg + SiO gas mixtures (Donn et al. 1981). Experiments were also carried out on Fe + SiO again with similar results.

2. Water Ice and Ice Mixtures

A different phase of low temperature research applicable to astrophysical problems is the study of condensed volatile species. This aspect deals with pure water ice and simulated cosmic ice mixtures.

A number of laboratory studies of the spectra of ices and ice mixtures has been carried out. Lebofsky and Fegley (1976) have provided the reflection spectra of several molecular frosts in the wavelength range 0.3-1 micron. Moore (1981) also shows the spectra from 2.5-15 microns of a variety of condensed molecules and mixtures. A similar collection of spectra was presented by Hagen et al. (1983) which includes the effect of changing concentration and temperature (permitting increasing degrees of diffusion in the sample). The spectra of hydrated frosts, over the wavelength range from 1-6 microns, has been studied by Smythe (1975).

A number of experiments have investigated the infrared spectrum of amorphous ice and applied the results to astronomical observations (Hagen et al., 1981; Leger et al., 1983, Kitta and Kratschmer, 1983). Extensive physiochemical experiments have been carried out on amorphous ice. These are reviewed by Sceats and Rice (1982).

In addition to water ice and ice mixtures, gas hydrates or clathrate hydrates have been proposed for interstellar grains or grain mantles although most of the emphasis of these experiments have been for comets. Miller (1961, 1973) reports experimental results for astrophysically interesting clathrates. Extensive reviews are given by Davidson (1973) and by van der Waals and Platteeuw (1959). Recent results are given by Cady (1983) and Davidson et al. (1984). An inability to directly condense clathrates below about 100K has been demonstrated and briefly discussed by Bertie and Devlin (1983).

A comprehensive presentation of the physics and chemistry of water, ice and aqueous solutions can be found in the series "Water - A Comprehensive Treatise" edited by Frank. Recent research on ice appears in the proceedings of the symposia "The Physics and Chemistry of Ice" (Riehl et al., 1969),

(Whalley et al., 1973), (J. of Glaciology, 1978) and the volume for the 1983 meeting.

Because matter in space is irradiated by ultraviolet photons and particles in the Kev or Mev range, experiments on ice irradiation have been carried out. A systematic program on ultraviolet irradiation of ice mixtures has been underway at Leiden University. An account of this work and many references to it are given in Greenberg (1982). At Goddard, the effect of 1 Mev protons on ice mixtures has been studied (Moore and Donn, 1983). At the Joffe Institute of Physics and Technology in Leningrad, experiments on the irradiation (Kaimakov et al., 1977) and vaporization of ice and ice-dust mixtures (Kaimakov and Sharkey, 1972; Lizunkova et al., 1977) have been carried out. Experiments on the photodetachment, photodissociation and photochemistry of ice mixtures have recently been performed at the Institute for Molecular Sciences in Japan (Nishi et al., 1984).

The references to experimental investigations have been colored by my interests. As pointed out in the beginning, this review is far from complete. A number of significant procedures are undoubtedly missing and important experimental studies are also omitted when particular techniques are mentioned. I apologize to the reader who may be misled by the first omission and to the investigators who were not given due credit by the second. Some of these deficiencies would have been avoided had I been able to attend this stimulating meeting but others were due to a desire to limit the size of the present work and to guide the reader to sources of data and additional references.

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CIRCUMSTELLAR DUST

Eli Dwek et al.

The presence of dust in the general interstellar medium is inferred from the extinction, polarization, and scattering of starlight; the presence of dark nebulae; interstellar depletions; the observed infrared emission around certain stars and various types of interstellar clouds. Interstellar grains are subject to various destruction mechanisms that reduce their size or even completely destroy them (e.g. Seab et al, this volume). A continuous source of newly-formed dust must therefore be present for dust to exist in the various phases of the interstellar medium (ISM).

This working group has the following goals: 1) review the evidences for the formation of dust in the various sources; 2) examine the clues to the nature and composition of the dust; 3) review the status of grain formation theories; 4) examine any evidence for the processing of the dust prior to its injection into the interstellar medium; and 5) estimate the relative contribution of the various sources to the interstellar dust population.

Sources considered in this report are: cool giant and supergiant stars, planetary nebulae, hot stars, evolved stars, novae, supernovae, and protostars. A brief review on observational aspects of circumstellar dust, and on the formation of circumstellar grains is given, respectively, by Jura and by Draine in this volume.

1. EVIDENCE FOR DUST FORMATION

The presence of dust in circumstellar shells around **cool evolved** stars is inferred from the infrared (IR) excess above the underlying stellar continuum or free-free emission, from the polarization of starlight, and from the presence of reflection nebulae surrounding the star. The IR excesses are apparent at wavelengths above 5 microns. They appear either as a continuum that exhibits a shallower falloff with increasing wavelength compared to the underlying stellar emission, or exhibit characteristic dust emission features.

In **planetary nebulae** the presence of dust is also inferred from the extinction and scattering of the stellar UV and optical emission. However, an unresolved issue is the phase in the evolution of the star during which the dust actually formed. The dust could have formed during the red giant phase, and been accumulated in a shell during the formation of the planetary nebula. Alternatively, the dust could have formed during the planetary ejection phase.

The presence of dust around **novae** is inferred from the evolution of their radiative output at the various wavelengths. A few months after the explosion, the nova light curve may exhibit a dramatic rise in the infrared which is concurrent with a rapid drop in the UV-visual (e.g. Gehrz et al., 1980 and references therein). The appearance of the infrared excess is usually interpreted as evidence for the formation of dust in the expanding novae ejecta (e.g. Clayton and Wickramasinghe, 1976). The appearance of the dust in the expanding shell is then also the cause for the drop in the observed UV output from the star. A different explanation was offered by Bode and Evans (1980a). They suggested that the dust around some novae was not formed during the nova event but during an earlier phase in the evolution of the progenitor star. The observed IR excess in their model therefore represents the reprocessing of the UV-visual output of the star by the preexisting circumstellar dust shell. The concurrent drop in the UV is more difficult to explain in their model, and is attributed to an increase in the effective temperature of the nova that is associated with its decreasing photospheric radius (Bath and Shaviv, 1976).

That dust formation may take place in **supernovae (SN)** is inferred from the presence of isotopic anomalies in meteorites (see D. D. Clayton, et al. in this volume). In the absence of an underlying source of UV emission, which provides the heating of the dust in novae, it may be impossible to obtain evidence for the formation of dust in the expanding SN ejecta from the evolution of the SN light curve. The excess of IR emission detected in three recent Type II supernovae (Merrill, 1979; Dwek et al., 1983; Graham et al., 1984) represents in all three cases the UV-visual outburst of the star reprocessed by circumstellar dust that presumably formed during the red giant phase of its evolution (Bode and Evans, 1980b; Dwek, 1983). Of the three supernovae

only SN 1980k was also consistent with the interpretation that dust formed in the SN ejecta (Dwek et al., 1983). Direct evidence for the existence of supernova condensates can be obtained by infrared observations of young, relatively unmixed supernova remnants (Dwek and Werner, 1981). Two such candidates are the Crab Nebula and the Cas A remnant, however, so far neither remnant shows any conclusive evidence that the observed dust is of supernova origin (Marsden et al., 1984, and Dwek et al. in preparation).

Protostars are observed to be embedded in cocoons of dust and were suggested by Field (1974) as major sources of interstellar dust. The observed circumstellar dust may, however, be preexisting dust from the protostellar environment out of which the star formed.

Evolved stars like R Coronae Borealis are extremely carbon-rich objects (C/H>>1) which periodically fade up to eight magnitudes in the visual. Typically after several months, they return to normal (Payne-Gaposchkin, 1963; Alexander et al., 1972). Subsequent to the discovery of an IR excess around R Coronae Borealis (RCB) (Stein et al., 1969) it has been generally accepted that dust is always present around RCB type stars. The fading of the star is attributed to the ejection of a cloud of carbon grains along our line of sight (O'Keefe, 1939; Forrest et al., 1972). UV observations of the star, and the derived UV extinction curves are consistent with that hypothesis (Hecht et al., 1984).

2. DUST COMPOSITION

Stars with circumstellar dust shells can be grouped into two main classes based on their photospheric abundances: those in which oxygen is more abundant than carbon (C/O<1), and those for which C/O>1. The dust type in the circumstellar shell seems well correlated with these two classes: silicate dust with oxygen-rich stars, and carbonaceous and SiC particles with carbon-rich stars.

The presence of silicates in oxygen-rich stars is inferred from the 9.7 and 18 micron emission features (e.g. Aitken, 1981), and the featureless

infrared spectrum observed in carbon stars and planetary nebulae (Mathis, 1978) is usually attributed to crystalline graphite. Draine (1984) predicted that crystalline graphite should have a resonance feature at 11.52 microns which has not yet been detected, and this may suggest that circumstellar carbon is instead amorphous. **SiC** has a broad emission feature extending from 10.5 to 13 microns which has been observed in circumstellar shells around carbon stars and some planetary nebulae (see review by Aitken, 1981). Based on cosmic abundances, it is expected that less than 10 percent of the dust around carbon-rich stars will be SiC. Therefore, SiC will be a minor contributor to the interstellar visual and UV extinction (Mathis, Rumpl, and Nordsieck, 1977). A broad 25-30 micron feature, seen in carbon stars and in carbon-rich planetary nebulae (Goebel and Moseley, 1985; Forrest, Houck, and McCarthy, 1981) was suggested by them to be a resonance feature in solid **MgS**. The feature is absent in planetary nebulae with high C/O ratios, suggesting that most of the sulphur in that case is locked up in CS.

A few oxygen-rich stars show absorption features at 3.1 microns and 6.0 microns (Soifer et al., 1981), which is characteristic of water ice at temperatures significantly lower than 150 K. These observations suggest that $\mathbf{H_2O}$ can condense out from the gas at sufficiently large distances from the star (see Jura, this volume). Additional evidence for the presence of circumstellar ice is suggested by the UV observations of HD 44179 (Sitko, Savage, and Mead, 1981), the illumination source for the Red Rectangle Nebula. The 1600 A absorption feature in the spectrum has been interpreted by Hecht and Nuth (1982) as evidence for the presence of water ice in the circumstellar shell of that star.

A variety of objects exhibit a series of "unidentified" infrared emission bands at 3.3, 6.2, 7.7, 8.6, and 11.3 microns (see review paper by Aitken, 1981). Recently, Leger and Puget (1984) suggested that these features arise from very small (50 atoms) hydrogenated carbon "grains", that are radiatively excited by the stellar UV radiation. **Polycyclic aromatic hydrocarbons** (PAH's) appear the most promising carriers of these features; however, the exact nature of the exitation mechanism is still controversial (Allamandola, Tielens, and Barker, 1985).

The presence of various elements and their isotopic composition in circumstellar dust grains can only be confirmed from the study of meteorites. Abundance anomalies in these objects suggest that volatile s-process elements, and short-lived radioactivities were trapped in circumstellar grains during the condensation process (see Clayton et al., this volume). The presence of these volatile elements in the grains provide a challenge for anyone attempting to model the condensation process in circumstellar shells.

The crystal structure of the emitting dust can affect the shape of dust emission features as well as the long wavelength behavior of the dust emissivity. This effect is most obvious in the comparison of the absorption efficiency of graphite particles (e.g. Draine and Lee, 1984) with that of amorphous carbon (e.g. Koike, Hasegawa, and Manabe, 1980). For silicates and other grain materials the differences may be more subtle. The shape of the 9.7 micron feature in circumstellar shells which is reasonably well fit by that of amorphous silicates (Papoular and Pegourie, 1983) appears different in red giant shells compared to the Trapezium (see Forrest, McCarthy, and Houck, 1979 and references therein), suggesting a different crystal structure in these regions. The significance of the difference is currently unclear, since uncertainties in the subtraction of the underlying continuum may be larger than the difference in the spectra. Additional information on the crystalline structure of grains may be inferred from the far-infrared behavior of their emissivity. An inverse square wavelength dependence is expected for crystalline particles. Recent observations (e.g. Sopka et al., 1985) suggest that the far-infrared drop in absorption efficiency of silicate or carbon grains appears to follow a wavelength $^{-1}$, or wavelength $^{-1.5}$ behavior, suggesting that these grains are amorphous. However, a distribution of grain temperatures will also have the effect of producing a flatter spectrum from an originally steeper one. More detailed observations are needed to distinguish between these two possibilities.

Additional evidence that circumstellar carbon may be amorphous, rather than crystalline graphite, is suggested by the 2400-2500 A bump in the UV extinction curves toward R Coronae Borealis stars. These stars are carbon-rich and hydrogen-poor with C/H ratios of about 100, in which graphite rather

than hydrocarbons should be very stable. However, an analysis of the extinction curve (Hecht et al., 1984) showed that the feature is consistent with the presence of glassy or amorphous carbon around these stars.

3. DUST FORMATION

Although the growth of interstellar dust grains may take place in the interstellar medium (see Snow this volume) the cores of these grains are probably formed in the various sources considered in section 1. Jura (this volume) summarized radio and infrared observations of cool giant stars that can provide observational constraints on theories for dust formation in the outflowing gas. These constraints include the physical properties of the gas, and the size and composition of the dust in the outflow. A summary of how these observational constraints mesh with current theories of circumstellar dust formation was presented by Draine (this volume).

The nucleation theory which is used to describe the formation and growth of particles in astrophysical environments makes a number of simplifying assumptions which may not be valid in circumstellar flows. These assumptions are: 1) that the vibrational temperature of the clusters and the kinetic temperature of the gas are the same; 2) that the chemical distinction between the various refractory gas phase constituents can be overlooked; 3) that free energies for "critical" cluster sizes can be estimated using their bulk properties; and finally 4) that the sticking efficiency of a particle is not affected by the latent heat released by the formation of the chemical bond at the grain surface.

These assumptions are still controversial, and there is evidence that some of them are incorrect in real astrophysical environments or under laboratory conditions (Nuth and Donn, 1981; Stephens and Bauer, 1981; Donn and Nuth, 1985). Well outside the stellar photosphere the molecular vibrational temperatures drop below the kinetic temperature of the ambient gas. This disequilibrium reduces the validity of condensation calculations. More specifically, the reduced vibrational temperature will contribute to the stability of clusters and may be a key factor in the onset of the nucleation process

(Nuth et al., 1985). Another problem encountered in real astronomical environments is that the relevant collisional timescales may be longer than the dynamical timescale of the system. This point was illustrated by Scalo and Slavsky (1980), who showed that the final products of the chemical reactions between major constituents of expanding circumstellar shells may be controlled by the reaction kinetics in the outflow. Isotopic anomalies found in meteorites suggest the inclusion of volatile elements in the dust that formed around red giant stars. Nucleation theory has to include the possibility of trapping volatile elements in the condensation process (Kothari et al., 1979). In addition to simplifications in the nucleation theory, models for the formation of circumstellar dust may have considerably simplified the physical conditions of the gas in the flow.

The complexity of the actual process of circumstellar dust formation can be illustrated by applying the theory to a well observed object. The application of classical nucleation theory to circumstellar gas flows yields the point in the flow beyond which these clusters become stable, and the growth and final size of the dust particles.

Infrared photometric data of Alpha Orionis (summarized by Jura in this volume) suggests that silicate dust (observed by its 9.7 micron emission feature) is formed and detectable outside of 10-100 stellar radii (10^{14}-10^{15} cm linear dimension). The density in a spherically symmetric outflow decreases with distance from the star. Consequently, if dust formation is defered to a distance of 10-20 stellar radii, the resulting grain size is much smaller than that inferred from observations (see Draine in this volume). These problems indicate that the flow around the star is significantly more complex than assumed in the calculations. It is possible that regions interior to 10-20 R_*, which do not clearly contain the "9.7 micron dust feature", may be comprised of dust progenitors (clusters) and molecular masers that reside in cool clumps ($T<1000K$; $n<10^{10}$ cm^{-3}) which in turn are embedded in a warm, chromospheric medium (T near 10^4K; n approximately 10^8 cm^{-3}). A condensation instability could produce these conditions near the star (see Stencel, 1985; also this volume). Such instability could also explain the

presence of dust around hot Wolf-Rayet stars that exhibit rapidly moving (3000 km/sec) outflows, or around high temperature (5000 K) R Corona Borealis stars.

In contrast to cool stars which may produce dust continuously in their outflow, novae only produce dust during sporadic outbursts. Dust formation seems, however, to be inhibited in "fast" novae, so called because they exhibit a rapid drop in their UV-visual output (e.g. Gehrz et al., 1980). Comparison between the various type novae may therefore provide the opportunity to examine the physical parameters that can facilitate (or inhibit) the formation of dust in their ejecta (Gallagher, 1977).

So far, dust has not been observed in supernova ejecta. However, it is expected that the dust formation process in these objects may be significantly different from that occuring around stars or novae. In the case of Type II supernovae, the collapse of the central core of the progenitor star leaves no underlying source of radiation so that the formation of the dust in the ejecta may be regulated by collisional, rather than radiative, processes. Furthermore, observations of Cas A and the Crab Nebula show that supernovae ejecta are inhomogeneous, with significant abundance variations between the clumps. The resulting condensation sequence and dust composition may therefore be quite different from those calculated for a uniformly expanding gas (see Clayton et al., this volume). The enhanced density in the clumps may facilitate the condensation process, and shield the newly-formed grains from reverse shocks that arise from the deceleration of the remnant.

4. PROCESSING OF THE DUST

After their formation and prior to their injection into the interstellar medium the newly-formed dust particles may be subject to various physical conditions that can reprocess them. Reheating of the dust particles can change their crystalline structure; accretion in the flow, various surface reactions, or UV processing can alter their composition; and collisions among themselves and with the ambient gas can alter their size distribution or completely destroy them.

Variations in grain composition, size, and morphology are reflected by changes in the central wavelength, strength, and shape of their characteristic infrared bands. For example, the emission peaks of crystalline silicates differ in wavelength and shape from the emission bands of amorphous silicates of the same composition (Stephens and Russell, 1979). Furthermore, the 8-25 micron spectrum of various laboratory-produced amorphous and partially crystallized silicates show, in addition to the well known 10 and 20 micron bands, weak features which may correspond to weak structures present in the infrared spectra of oxygen-rich stars (Nuth and Donn, 1982).

Evidence for changes in the grain size distribution around R Coronae Borealis stars was presented by Hecht et al. (1984). From the fading of the visual output they proposed that after formation the grains grow to approximately 0.1 micron. Subsequent collisions result in a MRN power-law distribution of sizes ranging from 0.005 to 0.060 microns.

Graphite particles can react with atomic or ionized hydrogen in the vicinity of HII regions if their temperature is above a critical temperature of about 110 K. Barlow (1983) proposed that chemical sputtering of carbon grains can form surface hydrocarbon complexes which may be responsible for the observed "unidentified" infrared emission features. UV irradiation can lead to similar results. The observations of these features on the boundary of HII regions and in planetary nebulae may therefore be evidence for radiative or collisional processes on the surface of carbon grains.

5. RELATIVE CONTRIBUTION TO THE ISM

The relative contribution of the various sources to the interstellar dust population is of considerable interest because of the different abundance peculiarities that can be locked in the dust during the condensation process. For example, silicates that formed in supernova ejecta will contain pure ^{16}O, and were suggested as the source of abundance anomalies in the meteorites. The relative contribution of each source to the interstellar dust population depends on the total amount of mass returned from that source to the ISM, on

the fraction of condensible elements in the ejecta, and on the efficiency with which these elements condense out of the gas phase.

The contribution of **Red Giant stars** to the interstellar dust population is perhaps the least uncertain. In red giant winds it is possible to derive the mass loss rate from the star. If the circumstellar gas is ionized the mass loss rate can be derived from the radio free-free emission. If the hydrogen in the flow is molecular then the mass loss rate can be derived from radio observations of minor constituents such as CO. Major uncertainties in these derivations are the CO/H_2 abundance, and the distance to the star. Total mass loss rates integrated over the galaxy are found to be about 0.3 M_{sun}/yr with equal contribution from O- and C-rich stars (Knapp and Morris, 1985). Adopting a gas-to-dust mass ratio of 100 in the flow, the galactic contribution to the interstellar dust population from red giant winds is approximately $3x10^{-3}$ M_{sun}/yr. The mass of dust in the wind can also be derived directly from infrared observations. Major uncertainties in this method are the infrared properties of the dust, and the dust temperature profile from the star.

Supernovae and novae. The contribution from these sources is less certain than the contribution from red giants. If the infrared echo detected from SN 1980k is due to dust that formed in the supernova ejecta (Dwek et al., 1983) then the total amount of dust produced in that event was about $10^{-5}M_{sun}$, which makes it a neglible contributor to the interstellar dust population. IRAS observations of the Crab Nebula (Marsden et al., 1984) show that the IR excess above the radio synchrotron emission from the nebula is very small. The excess translates into a dust mass of $(5-30)x10^{-3}M_{sun}$ in the nebula which is also too small to be significant on a galactic scale. IRAS observations of the supernova remnant of Cas A show a large infrared excess above the free-free continuum. A preliminary analysis of these observations (Dwek et al., in preparation) suggests that the mass of the emitting dust is between 0.1 and 0.6 M_{sun}. Adopting an average value in that range, and a frequency of "Cas A type" supernovae of 0.01/yr gives a total galactic dust production rate of $3x10^{-3}M_{sun}$/yr, comparable to the contribution from red giant winds.

The most convincing evidence that the sudden rise in the infrared emission observed in novae is due to dust formation is the concurrent drop in the UV output from the star. The mass of dust produced in a nova event can range from 10^{-4} to 10^{-5} M_{sun}, which for a frequency of 40 events a year gives a contribution of $(4-40)x10^{-4}M_{sun}/yr$ over the galaxy (e.g. Dwek and Scalo, 1980).

Planetary nebulae and protostars. Based on infrared photometric observations of a large number of planetary nebulae Cohen and Barlow (1974) concluded that these objects are dust deficient, i.e. the dust-to-gas mass ratio in planetary nebulae is smaller than its cosmic value of 0.01. An estimate the mass of the dust requires a detailed knowledge of the composition and size distribution of the emitting particles, since these properties determine the dust temperature in a given radiation field. Based on far-infrared observations of a number of planetary nebulae Moseley (1980) concluded that their dust-to-gas mass ratio is not significantly different from that of the ISM. The gas contribution from planetary nebulae to the ISM is about $4x10^{-2}$ M_{sun}/yr (Dwek and Scalo, 1980), which for a cosmic dust-to-gas mass ratio gives an upper limit to the galactic dust contribution of $4x10^{-4}M_{sun}/yr$.

The contribution of protostars to the interstellar dust population is hard to estimate. Protostars are observed to be enshrouded in cocoons of dust. The major uncertainty is the fraction of the dust that existed prior to the formation of the star. Assuming that half of the condensible elements in the protostellar nebulae existed in the gas phase Dwek and Scalo (1980) estimated the dust contribution of protostars to be $<3x10^{-4}M_{sun}/yr$.

Hot stars and evolved objects. Infrared excesses that can be attributed to circumstellar dust were only observed in Wolf-Rayet stars of type WC9 and some WC8's. Since these stars and other evolved objects are rare their contribution to the interstellar dust is not expected to be significant. Abbott (1982) estimated the gas mass loss rate from hot stars to be $0.03M_{sun}/yr$, giving a dust production rate $<3x10^{-4}M_{sun}/yr$.

6. PROSPECTS FOR FUTURE RESEARCH

A significant amount of observational, experimental, and theoretical work is still needed to resolve the various issues reviewed by this working group. The role of certain astronomical objects as dust sources is not yet resolved, and their contribution to the interstellar dust population is uncertain. The crystalline structure of the newly-formed dust is still subject to interpretations, and the degree of reprocessing in the circumstellar environment unclear. The identification of the carriers of the "unidentified" emission bands still needs to be firmly established, and details of the emission mechanism still need to be worked out. Details of the nucleation process are lacking, and we are ignorant about the astrophysical conditions in the condensation sites. More specifically, the following list of objectives may help resolve some of the issues mentioned above.

Extensive mapping of the infrared emission around planetary nebulae will establish the location of the dust with respect to the HII region and may resolve the question of whether the observed dust was preexisting material that was merely "pushed" out during the planetary ejection phase or whether it formed in the planetary nebula.

Supernovae may contribute as much dust to the interstellar medium as giant and supergiant stars. However the presence of dust in supernova ejecta has not yet been established. IRAS follow-up observations with high spatial resolution of young, unmixed, "Cas A type" supernova remnants will be an important step in that direction. High spectral resolution observations are needed to estimate the contribution of infrared emission lines to the observations. Coordinated infrared and optical searches for Type II supernovae are important if one hopes to observe the dust during its formation phase.

Spatial imaging, especially within a few tens of stellar radii, and the determination of dust and molecular abundances with distance (radial and azimuthal) is a useful observation to pursue. An evolutionary sequence ("atoms" to molecules to clusters to pregrains to grains) with distance from

the star will yield valuable information on the development of grains in the outflow.

Condensation experiments are needed to examine the validity of classical nucleation theory in astrophysical environments. Any alternative theory will have to include the possibility of trapping volatile elements in the condensing particles. A full kinetic nucleation model will require detailed transition rates between the various states of the system.

More observations are needed to characterize the physical conditions in the various condensation sites. The implication of these conditions for the nucleation process need to be examined. For example, many red giants and related stars are observed to pulsate and create slow shocks and density inhomogeneities in the outflow. The role of these shocks and inhomogeneities (if they persist in the flow) in the nucleation process is unclear.

Observations capable of detecting spatial or temporal variations in grain properties by means of variations in their spectral properties are critical to elucidating processing of circumstellar grains. Changes in the crystal structure of grains due to processing in a circumstellar environment may be monitored by narrow spectral band mapping of the circumstellar region at wavelengths centered on the amorphous and crystalline silicate bands. Changes in metal to silicon ratio of amorphous silicates introduces small spectral shifts which may be monitored using this technique.

Grain destruction in the ISM is predicted to be so efficient that it becomes difficult to account for the observed abundance of refractory grains in the ISM, or to account for the preservation of isotopic anomalies in the meteorites. The contribution of the various sources to the production of interstellar grains needs to be reexamined. Of special importance are supernovae which are noted for the overabundance of refractory elements in their ejecta. The contribution of protostellar nebulae is also very uncertain. Finally, methods of producing dust in the interstellar medium (Elmegreen, 1981) or in dense cloud cores, need further investigation. On the other hand, the efficiency for grain destruction may be lower than currently estimated.

The dynamics and the destruction of the dust in various types of astrophysical shocks need to be reexamined in more detail.

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INTERSTELLAR GRAINS

T. P. Snow et. al.

There are few aspects of interstellar grains that can be unambiguously defined. Very little can be said that is independent of models or presuppositions; hence this report will primarily raise issues and categorize questions, rather than providing definitive answers.

The questions and issues that have arisen during the conference fall into three general areas: (1) the general physical and chemical nature of the grains; (2) the processes by which they are formed and destroyed; and (3) future observational approaches to (1) and (2). A fourth category, discussion of alternative models for the grains, could be added, but the models have been well described in this volume by Mathis, and the reader may judge how well the data summarized here compare with the models.

As an introduction, though, certain general characteristics of the interstellar medium (ISM) need to be mentioned. There are several types of environments, distinguished on the basis of density and temperatures: (1) dark clouds, constituting the majority of the mass in the ISM, having densities over 10^3 particles per cm^3 and temperatures below 50K; diffuse clouds, containing perhaps 25-50 percent of the mass, characterized by densities of $1-100/cm^3$ and T in the range 50-100K; "intercloud" gas (which may actually represent the surfaces of diffuse clouds), containing between 1 and 30 percent of the mass, with densities of roughly $1/cm^3$ and T near 10^3K; and the so-called coronal gas, containing insignificant quantities of mass (but filling most of the volume of the ISM) with n of $10^{-2}/cm^3$ and T on the order of 10^{5-6}K. Grains are detectable in the first three of these environments. The greatest quantity of information comes from those in the dark clouds and the diffuse clouds. Hence, this report will concentrate on these two environments, but it is worth noting here that attempts to detect and analyze grains in the other regimes of the ISM would be of interest.

I. THE PHYSICAL AND CHEMICAL NATURE OF INTERSTELLAR GRAINS

Based on observations and relatively model-free interpretations, we can specify several important aspects of interstellar grains, and raise questions associated with each.

Scattering theory indicates that grains represent roughly 1 percent of the mass in the interstellar medium. This value is consistent with the fraction of the mass that is depleted from the diffuse interstellar gas, so it is thought that rather little diffuse-cloud mass is tied up in grains (such as very large particles) that do not affect interstellar extinction, or in molecules.

From the observed scattering and extinction properties of interstellar grains, it is clear that there must be a range of sizes. The precise size distribution is not well known. The review by Mathis in this volume discusses several alternatives which have been suggested. Infrared data from reflection nebulae (Sellgren, 1984; Witt et al., 1984) indicate that the size distribution extends to very small (<100A) grains, but it is not known what the lower limit on grain sizes is, nor whether in fact the distribution represents distinct populations rather than a continuum. (There is, in fact, a substantial question about the distinction between large molecules and small grains for typical sizes below 100A).

The narrowing of the linear polarization curve in dense clouds (Wilking, Lebofsky, and Rieke, 1982) indicates a reduction in the range of particle sizes, as would be expected if grains coagulate in the clouds or if the grains grow mantles which are thick in comparison to the cores (Aannestad and Greenberg, 1983). Scattering data in the infrared (for clumps around IRc2 in OMC-1) indicate that grain sizes in dark clouds are substantially larger than in diffuse clouds and could typically be a fraction of a micron (Ronan and Leger, 1984).

Little is known definitively about the composition of interstellar grains, but cosmic abundances impose severe constraints. The 9.7 micron emis-

sion feature probably shows that silicates are present and it has been argued that organic material is also present (Allen and Wickramasinge, 1981; Allamandola, 1984). Other spectroscopic indicators are ambiguous or unidentified. Grains containing graphite are suspected to be present, since carbon stars are rich sources of grains. Graphite may account for the 2175A extinction feature, but there are difficulties in this interpretation. One problem is that a plausible variation in the size distribution for graphite grains (Mathis, Rumpl, and Nordsieck, 1977) should produce a range of bump wavelengths that is not observed; another problem is that the bump is absent (and replaced by a feature near 2400A) in the best-observed carbon star (R Cr B; Hecht et al., 1984).

Observations of circular and linear polarization due to grains (Martin and Angel, 1977) indicate that the polarizing grains are dielectric in nature, implying that they are nearly pure scatterers. On the other hand, data on extinction in emission nebulae (Israel and Kennicutt, 1980) and on scattering in reflection nebulae indicate that some absorption occurs. Models of reflection nebulae (Witt and Cottrell, 1980) show that typical grain albedos are roughly 0.6. This is consistent with infrared emission data from IRAS as well, but is inconsistent with the requirement that dielectric (i.e., purely scattering, non-absorbing) grains produce the observed polarization. Hence, the evidence is strong that at least two distinct types of grains contribute visible-wavelength polarization and extinction. Other data may show a significant shift in the scattering phase function between visible and ultraviolet wavelengths, so a third distinct population, responsible for extinction in the ultraviolet, seems also to be present.

Studies of grain formation (discussed in Section II below) indicate that there are at least two distinct environments in which formation may occur: (1) oxygen-rich environments, yielding grain compositions dominated by silicates or oxides; and (2) carbon-rich environments, producing grains made of pure carbon or carbon compounds such as SiC. This picture may be consistent with the independent evidence (cited above) for distinct grain populations, but few observational tests can be made. Evidently, the different grain popu-

lations are rather well mixed in the interstellar medium, so it is difficult to associate specific grain origins with specific observable grain properties.

Beyond the general assumption that there are silicate grains and carbon grains in the diffuse medium, very little specific information is available on grain compositions. One possibility is "quenched carbonaceous condensate", produced in the laboratory, which shows a 2175A feature (Sakata et al., 1984). Another very recent suggestion, consistent with near-infrared photometric data indicating the presence of a population of very tiny grains, is that polycyclic aromatic hydrocarbons (PAH's) exist in abundance (Leger and Puget, 1984). These molecules may be viewed as constituents of graphite particles. They may account for several previously unidentified infrared emission features in emission and reflection nebulae (although molecular vibrational transitions induced by charged grains have also been suggested (Puetter, this volume)) and in solid form (as on grain mantles) they may also play a role in creating the broad near-IR emission observed in several reflection nebulae (Wdowiak, this volume). Furthermore, they may also explain the emission in the 12 micron band by the "interstellar cirrus" clouds discovered by IRAS (Leger, this volume; although thermal emission by tiny silicates is another possibility), and appear potentially interesting as candidates for the carriers of the confounding unidentified diffuse interstellar bands (DIB's) in the visible (Leger and d'Hendecourt, 1985; van der Zwet and Allamandola, 1985; Crawford, Tielens and Allamandola, 1985).

The potential for PAH's is tempered, however, by a lack of information. It remains to be seen how well they will withstand more careful scrutiny. For example, little is known about the detailed spectra of specific species, and quantitative measurements of their ultraviolet extinction properties are available for only a few relevent species.

Summary of key questions:

1. **Grain Size Distribution:** It is important to know how small and how abundant grains are at the small end of the distribution. This has important implications for the observed near-IR broadband emissions from some regions,

and for the surface area available for depletion and for other surface processes such as H_2 formation.

2. Grain Composition: Is there graphite in the interstellar medium, or not? Meteoritic data suggests that there may not be (Nuth, this volume). In either case, how do we account for the invariability of the 2175A extinction feature, since shifts in wavelength are expected if it is due to a continuum of grains? How much graphite is needed to produce the 2175A feature and how well-ordered must its structure be? Can we find regions dominated by either carbon-rich or oxygen-rich grains, so that we can directly associate grain properties with grain origins? Do polycyclic aromatic hydrocarbons or quenched carbonaceous condensates exist in the interstellar medium? Can we explain the simultaneous indications that visible polarization is produced by pure scatterers, while visible extinction is in part due to absorption?

II. GRAIN FORMATION AND DESTRUCTION

Analysis of grain formation rates (in the atmospheres of red giants and in supernovae) shows that the entire mass of galactic dust and gas population can be produced in about 3×10^9 years. On the other hand, grain destruction in shocks apparently can destroy grains in 10^8 years (Draine and Salpeter, 1979; Dwek and Scalo, 1980; Seab and Shull, 1983). This indicates that there must be an additional source of grains, in order to maintain the observed population. The only suggested additional source is the growth of grains by accretion onto small seeds in dense interstellar clouds (Draine, 1984; Greenberg, 1984). There is substantial observational evidence, in the form of measured depletions and IR absorption due to icy grain mantles, that grains can grow due to accretion of material from the gas. There are substantial questions, however, about the source of nucleation seeds for such growth, about the timescale on which the growth occurs, and about whether such growth can produce grains with all the observed properties.

Nucleation seeds may be available from shock processing of grains, if the grains are broken into fragments rather than being fully vaporized. Constraints can be placed on this by observations of shocked gas, which show that

most of the grain material is vaporized in high-velocity shocks (as indicated by the lack of depletion in shocked gas (e.g. Shull and York, 1977; Snow and Meyers, 1979). Lower-velocity shocks may, however, break grains into pieces without fully vaporizing them.

The timescale for grain growth in interstellar clouds depends on the available surface area; recent indications that a large number of very small grains are present (Sellgren, 1984; Draine and Anderson, 1985) have substantially increased the estimated surface area, and hence, have reduced the grain-growth timescales to reasonable values.

Potentially difficult aspects of grain growth in the interstellar medium have to do with the observational constraints placed on the resulting grains. Several specific grain features must be reproduced by grains grown in the interstellar medium. For example, the 9.7 micron feature indicates the presence of silicates, which might be formed by condensation at high temperature in a stellar atmosphere, but which may be more difficult to form from the deposition of silicon atoms onto cold grains in the presence of hydrogen. Amorphous films of SiO and Mg + SiO have been grown in argon matrices at 50K. These films have infrared absorption properties which resemble interstellar silicates (Stranz et al., 1981; Donn et al., 1981). It is noteworthy in this context that virtually all silicon in the diffuse ISM is in the grains, so the process of grain growth in the ISM must be very efficient. Also, the analysis of interplanetary material reveals isotopic ratios that probably were created by r-process (supernova) or s-process (stellar atmospheres) during circumstellar grain formation, and which would be very difficult or impossible to recreate in grains grown by accretion in the interstellar medium. This implies that some fraction of the interstellar grains present when the solar system formed were pristine products of the formation processes in supernovae or stellar atmospheres, and had not been destroyed and regrown in interstellar environments. Also, as noted in Section II, there apparently are distinct grain populations, as evidenced by scattering and polarization analyses. It is possible to attribute these to distinct formation environments if grains are produced in stars or supernovae, but this is not so easy to do if grains are grown in the ISM. Perhaps the distinct populations arise from nucleation

cores with distinct compositions and differing abilities to grow or retain mantles.

Apart from the general question of grain formation rates versus grain destruction rates, more specific information is available on grain growth. There is a general pattern of elemental depletions indicating that certain elements (generally refractories) are more highly concentrated in grains than others. It is not clear whether this pattern is due to selective accretion of refractories onto grains, to selective sputtering or photodesorption of volatiles off of grains, or to a grain formation process in which the refractory elements are bound into grain cores. Possibly all four processes are at work. It is clear that accretion onto grains does occur; that the overall level of depletion correlates at least roughly with cloud density (although the evidence for this is not as strong as commonly supposed; curve-of-growth ambiguities due to line saturation on one hand, and regional variations on the other apparently conspire to enhance the appearance of a correlation).

A grain growth process that competes with mantle accretion is the coagulation of grains, as implied by the low ratio of scattering optical depth to grain mass that characterizes certain diffuse clouds (Jura, 1980; Mathis and Wallenhorst, 1981), and by the particle size distribution in dark clouds inferred from infrared scattering studies (Ronan and Leger, 1984). This process has no effect on depletions, however, and so it cannot explain the enhanced overall depletions in dense clouds. Hence, grain growth must occur in dark clouds both by the accretion of mantles as well as by coagulation. Evidence for mantle growth is found in the 3.1 micron water ice feature and in many other bands (e.g. Hagen et al., 1980; Tielens et al., 1984, 1985; Allamandola, 1984; Kitta and Kratschmer, 1983). A quantitative analysis of the mantle features in one line of sight (W33) implies that 30% of the carbon and oxygen are in grain mantles.

Summary of key questions:

1. **Formation And Destruction Rates:** Is the timescale for grain destruction really shorter than that for grain formation in supernovae and stel-

lar atmospheres? If so, then great difficulty arises in finding a way to grow grains in the interstellar medium with all the observed properties. More specifically, what is the source of nucleation cores, and how does grain growth produce grains capable of creating the observed polarization, silicate emission, silicon (and other) depletions, isotopic ratios, and distinct grain populations?

2. **Depletions:** What are the relative roles of grain formation, selective accretion, and selective sputtering and photodesorption in creating the observed pattern of depletions? Which grains are responsible for the depletions: is it a simple matter of surface area, which favors the abundant small grains, or is there a strong dependence on grain composition, temperature, charge, or other factors?

3. **Grain Chemistry:** What is the chemistry that produces the variety of mantles seen in dense clouds? What fraction of the simple molecules in accretion mantles can be converted to large molecular residues? What is the dominant conversion mechanism?

III. FUTURE RESEARCH

It is fitting that some discussion of future research directions be included here. This discussion will be partially redundant with the foregoing, but it seems worthwhile to try to systematically collect future strategies in one place.

1. **The 2175A Extinction Feature:** The invariance of the wavelength of this feature (to within a few tens of A) is established, but it is important to refine this measurement further. There remains the possibility of finding a dependence of the bump strength on some physical or chemical parameter that might help to identify its origin. For example, it has been attributed to graphite, but so far there is no clear-cut definition of what this really means. Specifically, does carbon have to be highly ordered, as is normally assumed, or is partial ordering sufficient? If the feature is due to carbon in some form, perhaps it should be enhanced in carbon-rich environments, but

not in grains formed in oxygen-rich environments. If so, it would be very helpful to try to isolate both types of environments and to see whether the feature is associated with one and not the other (this is being pursued for planetary nebulae). Another approach is to see whether carbon depletion from the gas correlates with bump strength. Studies of mantle growth and bump strengths may also be helpful. A couple of clouds have been formed in which the 2175A feature is strongly suppressed, and it has been suggested that mantle growth is responsible. Further study of these or similar cases may help reveal what has happened to modify the dust so that the feature is absent. A more sensitive search for the predicted 11.5 micron graphite feature (Draine, 1984b) in dark clouds should be made. Finally, polarization structure (or the lack thereof) in the 2175A feature may help specify the carrier; data will be available within a year.

2. Spectroscopic Exploration Of Candidate Materials: Here there are several important considerations. First, it is essential to isolate specific compounds or molecules (as in the case of the PAH's) and measure their detailed spectra. Many close coincidences are already found, but that is not sufficient to establish the identity of observed interstellar features. This applies to the unidentified infrared emission bands, the broad red-near-IR emissions in reflection nebulae, and to the visible-wavelength diffuse interstellar bands. Second, predictions should be made, based on laboratory spectra, of interstellar features in wavelength regions not yet explored. Of great potential importance here is the tentative indications that proposed candidate materials, particularly the PAH's, have strong ultraviolet signatures. Extensive visible ultraviolet measurements of such materials are available for comparison (see references in Donn, 1968). The laboratory data should be translated into predicted ultraviolet extinction structure, so that quantitative comparisons can be made. Conversely, continued attempts at measuring structure in UV extinction curves should be made.

3. Polarization And Scattering Measurements: Models of interstellar grains should be extended to predict polarization properties in presently observed wavelengths. Again, the ultraviolet is important, and will be ob-

served within a year or so by the WUPPE experiment on the Space Shuttle. Also, grain shapes and grain alignment mechanisms should be studied further.

On the basis of polarization measurements, it should be possible to place lower limits on the ratio of the axes of grains in various environments. It should also be possible to distinguish between oblate and prolate grain shapes. In the case of silicate grains, for example, this can be done by comparing the wavelengths of maximum absorption and maximum polarization in the 10 and 20 micron absorption features (Lee and Draine, 1985).

Measurements on the high (or low) frequency side of the thermal emission peak of a cloud will favor detection of radiation from low (or high) emissivity grains. Polarimetry of the thermal emission at different wavelengths may therefore show correlations between grain properties related to temperature (dielectric constant and size) and those related to grain alignment and emission of polarized radiation (magnetic susceptibility and shape) (Hildebrand, 1983).

4. **Scattering Properties:** The analysis of scattering properties of grains, such as albedos and phase functions, can reveal a great deal about the size distribution and the presence or absence of distinct populations (as opposed to a continuum of sizes). Ambiguities about star-nebulae geometries, which plague present analyses, can be reduced by statistical studies of larger numbers of nebulae.

5. **Mantle Growth:** Laboratory measurements are capable of simulating mantle growth on grains and need to be pursued (Hagen et al., 1979). There are important questions having to do with mantle composition in particular, which require information on the surface physics. For example, hydrogen atoms collide with grains far more frequently than other species do, but the role of hydrogen on grain surfaces is not well known: does it desorb immediately, or does it dominate the chemistry of other elements? What is the role of ultraviolet photodesorption and photolysis?

In addition to continued laboratory work, astronomical observations relevant to grain mantles need to be extended. Better-quality infrared spectra from 2 to 14 microns are needed, as are better data on possible ultraviolet extinction features. There is very little data on the 3.4 micron absorption feature seen in diffuse ISM grains (Mathis, this volume).

The observation of polarized absorption (Jones et al., 1984) and polarized thermal emission from a cool dense cloud (Hildebrand, Dragovan, and Novak, 1984) shows either that the growth of grain mantles in such a cloud does not destroy the persistent surface features required for suprathermal rotation (Purcell, 1979), or that grains can be aligned by mechanisms not requiring suprathermal rotation. Duley (1978) has discussed alignment by ferromagnetic materials. Mathis (this volume) has quantitatively estimated the wavelength dependence of polarization of this mechanism. Alternatively, Greenberg et al. (1972) have suggested that radicals embedded in grain mantles could give grains "permanent" magnetic moments.

6. Depletions: Further explanation of the dependence of depletions on cloud physical conditions is needed. Improved accuracy in abundance determinations, requiring high S/N data at very high spectral resolution, should further clarify the process of grain destruction in shocks, which is very important in assessing the relative roles of grain formation and mantle accretion in creating the depletions in the first place. Another important approach is to make abundance and depletion measurements in dark clouds, something that is technology-limited but becoming more feasible.

7. Laboratory Experimentation: In addition to the chemical and spectroscopic experiments described in the foregoing sections, it would be useful to try to simulate physical processes that may affect grains in the interstellar environment. For example, it may be feasible to simulate grain-grain collisions to get real data on how grains are affected: what is required to fully atomize them; can they be broken up into small fragments but not atomized; does selective sputtering of elements occur; under what conditions does coagulation take place? What are the effects of very small grain sizes on

physical processes such as vaporization and mantle growth? How do UV photons affect surface processes?

Laboratory measurements of low-energy sputtering yields for candidate grain materials (both refractory and ice) are needed to check existing theoretical estimates for these yields. Measurements of photodesorption cross sections are required to clarify the role that ultraviolet radiation may play in selectively removing atoms and molecules which accrete onto grain surfaces in diffuse clouds. Photoelectric emission from dust grains plays an important role both in grain charging and in heating of interstellar gas; studies of photoelectric emission yields from small particles or thin films of candidate materials are therefore needed to model these processes.

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INTERSTELLAR MATERIAL IN THE SOLAR SYSTEM

John A. Wood et al.

All the substance of the earth and other terrestrial planets once existed in the form of interstellar grains and gas. A major aspect of solar system formation (and undoubtedly of star formation generally) is the complex series of processes that converted infalling interstellar grains into planets. A cryptic record of these processes is preserved in certain samples of planetary materials, such as chondritic meteorites, that have been preserved in a relatively unchanged form since the beginning.

It is to be expected that some of these primitive materials might contain or even consist of preserved presolar interstellar grains. The identification and study of such grains, the ancestors of our planetary system, is a matter of intense interest. This Section briefly discusses the types of primitive material accessible to us, or potentially accessible, and its component of or relationship to presolar interstellar grains.

GRAINS ACCRETING FROM THE INTERSTELLAR MEDIUM TO THE SOLAR SYSTEM IN THE PRESENT EPOCH

The planets sweep up a certain amount of dust directly from interstellar space as the solar system moves through the galaxy. The solar system is currently surrounded by interstellar material of average density 0.1 H atom/cm^3, and temperature 12,000 K. It may be 50% ionized. With respect to the sun this material is moving at 25 km/sec. The velocity vector of the sun suggests that it has been embedded in material of this density for 25 million years.

For a hydrogen-to-dust mass ratio of 100/1 and assuming grain radii of 0.01 microns and densities of 3 g/cm^3, the local dust density would be 10^{-10} grains/cm^3. If these impinging grains penetrate the heliopause, the solar wind, and the magnetopause without destruction, and have their orbits determined only by the gravitational field of the sun, we might expect the density

at 1 AU to be enhanced by gravitational focusing by factors of 3-10, yielding a maximum grain density near the earth of 10^{-9} cm^{-3}. Since the maximum motion of the earth relative to the cloud (when Earth's orbital motion is counter to the particle flux) is 55 km/sec, this would yield a maximum interstellar grain flux at the top of the earth's atmosphere of 6×10^{-3} cm^{-2} sec^{-1}. This is a substantial flux in terms of numbers, but the increment of mass is very small: it would amount to only 1 mg per cm^2 of the earth's surface over the age of the solar system in the unlikely event that the earth had always been immersed in its present low density region of interstellar space. (This estimate does not take into account the interaction of the solar wind with charged grains, or the influence of solar radiation pressure. It is possible that these effects would substantially change the rate of accretion of interstellar particles to the earth.) Thus recently-arrived interstellar dust constitutes only a miniscule fraction ($<10^{-4}$) of the extraterrestrial dust swept up by the earth each year ($>10^4$ tons; McDonnell, 1978).

INTERPLANETARY DUST: PROPERTIES AND PROCESSES

Information on the interplanetary dust cloud has been obtained from zodiacal light observations, lunar microcrater statistics, dust experiments on spacecraft, meteor observations and laboratory simulation experiments. Here we are talking about particles in the size range 0.01 microns to 1 cm, having masses of 10^{-18} g to 1 g. In the following we review present knowledge of the interplanetary dust cloud and processes governing it. We will show that most of this dust is derived from comets, which constitute a reservoir of relatively unprocessed presolar interstellar grains. After its release from comets, this material may have experienced mutual collisions, and this may have altered the original properties of interstellar grains. In the final paragraph we discuss the possibilities of identifying and analyzing interstellar grains that traverse the solar system.

The flux of interplanetary dust particles at 1 AU has been established from measurements of the lunar microcrater frequency, calibrated by spacecraft particle-impact experiments. For the larger particles, meteor observations provide an important source of information. The cumulative flux of the larger

particles (m> 10^{-6} g) is an exponential distribution proportional to $m^{-1.34}$. The midrange particle flux (10^{-12} g<m<10^{-8} g) is flatter, going as $m^{-0.36}$. The small-particle flux steepens up again and is proportional to $m^{-0.85}$ (for a recent review, see Grün _et al._, 1985).

The spatial distribution of interplanetary dust grains is obtained from observations of the zodiacal light (most of which is reflected from particles in the size range 10 microns to 1000 microns, _i.e._, 10^{-9} g to 10^{-3} g), and from _in situ_ experiments on deep space probes (which encounter particles mostly in the size range 0.1 microns to 10 microns, _i.e._, 10^{-15} g to 10^{-9} g). Inside 1 AU the spatial density of interplanetary particles increases proportional to $r^{-1.3}$, where r is the distance to the sun. This increase continues to at least inside 0.1 AU. Outside 1 AU the radial dependence is somewhat steeper ($r^{-1.5}$) to about 3 AU. Outside this distance little is known. The spatial density of small grains (m<10^{-9} g) may be constant or only very slowly decreasing out to 20 AU (Pioneer 10).

The major processes presently acting on interplanetary grains are mutual collisions, the Poynting-Robertson effect, and radiation pressure ejection of small meteoroids. These effects act differently on particles of the different size regimes. At 1 AU big meteor particles (m>10^{-5} g) are believed to be most affected by mutual collisions. The lifetimes are shortest (10^{4} years) for particles of masses 10^{-3} g to 1 g. The Poynting-Robertson lifetimes are at least a factor 100 longer for these particles. These large particles will not change their orbits significantly due to Poynting-Robertson effects before they are involved in a collision and fragmented into smaller particles. Only smaller zodiacal light particles (m<10^{-5} g) will have their orbits circularized by Poynting-Robertson drag and will eventually spiral in towards the sun, where they evaporate. Even smaller particles (m<10^{-12}) are affected by radiation pressure, which counteracts gravitational attraction. Such small particles, which are generated by collisions between larger parent meteoroids or which are released from comets, will generally follow unbound trajectories out of the solar system. Because of its short lifetime with respect to collisions (10^{4} yr), this meteor-sized particle population needs a steady supply from comets throughout the solar system. Collisions among main belt asteroids do

not seem to play a major role in supplying small meteoroids ($m<1$ g) to the Earth and the inner solar system.

The origin of the majority of large particles ($m>10^{-5}$ g) is comets. Meteor streams are clearly derived from comets. Even sporadic meteors have somewhat related orbits which indicate a cometary origin. The majority of zodiacal light (10^{-10} g to 10^{-5} g) particles are fragments from larger meteor-sized particles, the collisions of which are adequate to account for their source. The smallest interplanetary particles ($m<10^{-12}$ g) also originate from collisions of meteor-sized particles, for the most part, though in extended cometary tails the small particle population may be dominated by primary particles shed by the nucleus.

The interstellar particles that penetrate the solar system (discussed above) constitute only a small fraction of the small particle population. Orbital information from in situ experiments on Pioneer 8, 9, and Helios indicate that <10% of the observed particles have orbits compatible with an interstellar source. The upcoming International Solar Polar Mission will attempt to measure the interstellar component of particles above the ecliptic plane. With existing technology it is feasible to build a new dedicated experiment that would measure the flux and size distribution of IS grains entering the solar system. When techniques for measuring precise orbital parameters of particles are refined, it will be possible to actually collect particles that can be proven to be extrasolar on the basis of their hyperbolic orbits. Collection will be made with the techniques used on the Long Duration Exposure Facility and developed for the Flyby Comet-Coma-Sample Return mission.

INTERPLANETARY DUST: PARTICLES COLLECTED ON EARTH AND STUDIED INDIVIDUALLY

Debris from comets and asteroids exists as interplanetary dust for only 10^4 yr before being destroyed by collisions and Poynting-Robertson drag. Large numbers of dust particles are swept up by the earth, and their collection and analysis provides a means of investigating a variety of primitive asteroidal and cometary bodies that may not be represented by samples in the existing inventory of conventional meteorites. Of particular importance is

the high probability that many of the collected dust particles are samples of comets, bodies that accreted under very cold conditions and in which presolar IS grains may be preserved.

Interplanetary dust particles (IDP) are collected in the stratosphere by high-altitude aircraft, and particles larger than 100 microns are collected from the ocean floor and from polar ice. All of these particles were strongly heated during stratospheric entry; only those smaller than 10 microns were not heated to more than 600 C. The collected particles probably represent debris from a large number of small parent bodies: they should not be considered to have a common origin. Each particle is an individual meteoritic object with an unknown origin. There is currently no criterion for distinguishing cometary from asteroidal particles. The extraterrestrial origin of the particles is proven by their content of cosmic ray tracks, implanted solar wind atoms, and (in the case of particles >200 microns) cosmogenic ^{26}Al, ^{10}Be, and ^{53}Mn, primordial noble gases (Rajan <u>et al.</u>, 1977; Hudson <u>et al.</u>, 1981), and large D/H fractionation ratios (Zinner <u>et al.</u>, 1983).

Particles collected from the stratosphere have diverse properties, consistent with their derivation from a number of discrete parent bodies. A common property of most of the particles is that they have chondritic (solar) elemental abundances of the involatile elements. Many of the particles that do not have this composition are single mineral grains with material of chondritic composition adhering to their surfaces, implying that the grains were originally embedded in chondritic material. The chondritic material is black, contains up to 5% carbon, and is often extremely fine grained. It is the only meteoritic material that has a truly chondritic composition on the micron size scale. Most of the chondritic particles are aggregates of grains ranging in size from <100 A to >1 micron, but there is diversity in structure and mineralogy among the aggregates.

Two distinct types are (a) rather nonporous particles composed primarily of hydrated silicates, and (b) extremely porous aggregates (Fig. 1). The latter class (chondritic porous aggregates or CPA's) are the most fragile of meteoritic materials; their physical properties are the most compatible with

those inferred for cometary meteors. The basic subunits of these aggregates are individual rounded grains in the size range 1000-5000 A, which are weakly attached to one another to form a highly porous structure. These constituent grains have widely differing compositions, and obviously did not form in equilibrium with each other.

IDP Mineralogy

The morphologies of some mineral grains in IDP's suggest that they condensed from a vapor (see below). Some of the rounded submicron grains are single minerals, while others are complex particles composed of tiny crystalline phases embedded in amorphous carbon. This unique material contains grains less than 100 A in size. No IDP (or meteorite) ever examined has been found to contain aggregates of rodlike or rounded core-mantle grains of the types that are commonly discussed as interstellar (IS) grain models. It is possible, however, that the submicron grains composed of tiny crystals embedded in carbon could be either metamorphosed IS grains, or that they might actually be rather well-preserved IS material. Graphite occurs in these materials, but only in trace amounts. Some of the graphite is probably formed by catalysis, because it occurs in association with other forms of carbon that appear to have formed by catalysis. Carbon is as abundant as Silicon (atomic proportions) in IDP's, but the bulk of it is in the form of an amorphous phase that occurs both as coatings on grains and as pure grains several thousand Angstroms in size.

An overriding characteristic of the minerals in IDP's is their very small grain size. Consequently, few of the standard techniques of mineralogical analysis are readily applicable. The best method for the study of individual grains is Analytical Electron Microscopy (AEM) in its various aspects. Details of grain morphology are obtained by imaging, structure by electron diffraction (either selected-area or convergent-beam electron diffraction), and composition by energy-dispersive x-ray emission spectroscopy for elements of atomic number (Z)10 or greater and electron energy-loss spectroscopy for the lighter elements. The AEM thus offers a complete tool for mineralogical characterization on an individual crystal basis (although it does not provide

isotopic, trace element, or spectroscopic data). Major problems arise from sample preparation, radiation damage within the instrument, and the need for critical tilting of the specimen--in some cases beyond the operational capabilities of available instruments. Thus while AEM is in many ways an ideal technique for achieving the goal of understanding IDP mineralogy, it is a difficult technique with distinct limitations.

The carbonaceous material noted above may be present in IDP's as "clumpy masses" (Christofferson and Buseck, 1984; Rietmeijer and Mackinnon, 1985a), as coatings on mineral grains (Bradley *et al.*, 1983a; Mackinnon and Rietmeijer, 1984; Mackinnon *et al.*, 1985), and as filamentary grains. The latter may have been formed by heterogeneous catalysis reactions (Christofferson and Buseck, 1983; Bradley *et al.*, 1984). Some "clumpy masses" may be hydrocarbon compounds (Christofferson and Buseck, 1983). Detailed knowledge of the nature of these hydrocarbon compounds, especially their isotopic signature, will be needed to understand their origin or chemical evolution. The majority of the "clumpy masses" forms stacks of many thin (0.01 micron) plates. Individual plates are decorated with very finely granular carbonaceous material. The granules sometimes form clusters with an open fluffy texture. The morphology and crystallographic properties of these "clumpy masses" are consistent with those of poorly graphitized carbon (PGC; Rietmeijer and Mackinnon, 1985a). Micro-Raman spectra of individual IDP's show double peaks at 1350 and 1600 cm^{-1} that are characteristic of "disordered" graphite (Fraundorf *et al.*, 1982). PGC in CPA's constitutes a link with carbonaceous chondrites, as PGC with similar properties has been observed in acid residues of these meteorites (Lumpkin, 1983; Smith and Buseck, 1981, 1982).

Mg-rich olivine and enstatite, which are abundant in chondritic meteorites, are also observed in chondritic IDP's, though in the latter they display a narrower compositional range. Fassaite (Ca, Al-rich clinopyroxene) has been observed in one IDP (Tomeoka and Buseck, 1985a).

In general, chondritic IDP's are heterogeneous, non-equilibrium mixtures of both high- and low-temperature minerals. The low-temperature minerals may include layer silicates (Brownlee, 1978, Tomeoka and Buseck, 1984, 1985a,

1985b; Rietmeijer and Mackinnon, 1985b). These layer silicates include members of the smectite or mica group (Tomeoka and Buseck, 1984), and possibly also Mg-poor talc and kaolinite (Rietmeijer and Mackinnon, 1985b) and serpentine or chamosite (Brownlee, 1978). The layer silicates in chondritic IDP's are not similar to the principal layer silicates in C2 chondrite matrices, and they are also dissimilar to C1 chondrite phyllosilicates (Rietmeijer and Mackinnon, 1985b). These AEM observations contradict the conclusion of Fraundorf et al. (1981), from their infrared spectroscopy study of chondritic IDP's and C2 chondrite matrices, that layer silicates in both materials are similar. The discrepancy probably results from the difficulty of interpreting the IR spectra of very-fine-grained crystalline aggregates (Rietmeijer et al., 1985).

Most of the minerals in IDP's are similar to terrestrial minerals and/or those found in carbonaceous chondrites. However, IDP's also contain unusual minerals: some that were previously known, though rare, and others that are unknown except in IDP's. It is remarkable that the limited studies performed on IDP's have turned up as many unusual phases as they have. Two minerals have been found to date that are unknown except in IDP's, a carbide and a sulfide.

E-carbide has a composition between Fe_3C and Ni_3C (in approximate proportions of 8:1; Christofferson and Buseck, 1983; Bradley et al., 1984) in two different IDP's. Although it is only a minor constituent of IDP's, this mineral is of special interest because it is a possible residue of the catalytic conversion of H_2 and CO to hydrocarbons by Fischer-Tropsch (F-T) reactions. Such a catalytic conversion process has been proposed by Anders and colleagues (Studier et al., 1968) as a solution of the long-standing problem of formation of the wide range of hydrocarbons that occur in certain carbonaceous chondrite meteorites. However, there was no evidence in these meteorites that such catalysis occurred, other than the hydrocarbons themselves. E-carbide is known terrestrially to be a product of F-T synthesis, and thus its presence in IDP's lends additional credibility to the proposals of Studier et al.

Sulfides are common constituents of IDP's, but most occurrences are the common minerals troilite (FeS), pyrrhotite ($Fe_{1-x}S$), and pentlandite, ($[Fe,Ni]_9S_8$). The LOW-CA IDP contains all of these and, in addition, a mineral having the pentlandite structure, but a unique composition (Tomeoka and Buseck, 1984). It differs from normal pentlandite in that it contains less than 3 atomic percent Ni, whereas normal pentlandite contains over 20 atomic percent Ni. This low-Ni pentlandite has been synthesized by deposition from a vapor at <200 C, but is not known from the natural environment (meteoritic or terrestrial).

The presence of carbonates was recently confirmed by electron microscope studies of the CALRISSIAN IDP (Tomeoka and Buseck, 1985b), where it forms in well-developed euhedral crystals having the calcite structure and compositions ranging between $FeCO_3$ and $MgCO_3$.

A number of minerals in the IDP's have unusual morphologies that are possibly indicative of vapor-phase formation. The whisker crystals and platelets of enstatite described by Bradley et al. (1983b) are strongly suggestive of such an origin. The unusual morphology as well as the anomalous direction of elongation are characteristic of vapor deposition. Platelets of other minerals that are normally more equidimensional have been found in other IDP's. These include flat plates of olivine in U2001E3, and of magnetite and chromite (Christofferson and Buseck, 1984, 1985), and plates of pentlandite and especially low-Ni pentlandite in LOW-CA (Tomeoka and Buseck, 1984). While these unusual morphologies are not proof of vapor deposition, they are expressed in isometric or orthorhombic minerals that normally have very different morphologies. (Platelets of magnetite also occur in the matrices of carbonaceous chondrites, but here the morphology has been ascribed to aqueous alteration rather than vapor deposition.)

Optical Properties

Detailed infrared absorption measurements in the wavelength region 3 to 20 microns have been made on over two dozen particles. The experimental results and their implications are discussed by Sandford and Walker (1985).

The earliest work (Fraundorf et al., 1980) showed that the spectrum of an ensemble of three particles was dominated by a strong absorption at 10 microns. Subsequent work has shown that almost all particles fall into three major categories, labelled "olivine", "pyroxene", and "layer-lattice silicate," based on their spectral similarities to terrestrial mineral standards. Detailed transmission electron microscope investigations of several selected particles have confirmed that the actual mineral assemblages are, indeed, dominated by the minerals identified by the infrared absorptions.

Comparison with the dust spectrum of comet Kohoutek determined by Merrill indicates both similarities and differences with the particle data; a reasonable fit to the comet spectrum is obtained by combining the spectra obtained from the pyroxene and layer-lattice silicate classes. However, the fit is much worse when particles of the olivine class are included. It would appear that the infrared properties of the particles can be made to fit the comet data, but only at the expense of including particles with very different mineralogies (pyroxenes and layer lattice silicate classes) and excluding particles that are known to be extraterrestrial (the olivine class). Thus the optical data are not straightforwardly consistent with a cometary origin of interplanetary dust.

Comparison of the dust spectra with astronomical observations of protostars show some interesting similarities and raise some questions to be answered by future research. In addition to the dominant 10 micron feature in their spectra (commonly ascribed to absorption by amorphous Mg,Fe silicate dust), both protostars and particles in the hydrated silicate class exhibit a ubiquitous feature at 6.8 microns. In one IDP, CALRISSIAN, the 6.8 micron band is actually stronger than the 10 micron band. The presence in this particle of a substantially weaker band at 11.3 microns indicates that the 6.8 micron band is due to a carbonate mineral. As noted above, detailed electron diffraction measurements and imaging of this particle (Tomeoka and Buseck, 1985b) confirm that it contains abundant Fe and Mg carbonates. It is possible, but not proven, that the 6.8 micron band seen in other particles of the same spectral class are also due to the presence of carbonates. Although the carbonate identification is virtually certain in the case of this one IDP, it

remains an open and interesting question whether the band seen in protostars has, at least in part, a similar explanation.

Isotopic Compositions

Although the small size of interplanetary dust particles makes measurement a distinct challenge, isotopic measurements on major elements have been made. The first results were reported by Esat et al. (1979). Individual particles were studied in a thermal ionization source mass spectrometer, using a direct loading technique. Data were obtained on both Mg and Ca isotopes for 13 samples. The Mg isotopic composition of one particle was found to be highly mass fractionated (1.1% per amu). The measured Ca isotopic composition was the same as terrestrial Ca to within 2 percent.

In 1983 Zinner et al. showed that the D/H ratios in several particles were very much higher than in terrestrial samples. Values up to delD+2000 o/oo* were found. These data were obtained with an ion microprobe, an instrument capable of measuring isotopes on sub-fragments of an IDP several microns in size. Subsequent work by Zinner and McKeegan (1984) demonstrated that the D/H signature was highly variable from one part of a given particle to the next. The excess deuterium was also found to be correlated with the concentration of C, but not OH, indicating that the carrier was probably a carbonaceous phase.

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$$\mathrm{delD} = \left[\frac{(D/H)_{\mathrm{sample}}}{(D/H)_{\mathrm{standard}}} - 1\right] \times 1000;$$

typical range of terrestrial samples is delD = ±200 per mil (o/oo)

Carbon isotopic data were also obtained for several particles. Differences between particles of up to 40 $^{o}/oo$ were noted. This is a small effect, but outside the expected errors in the measurement. In contrast to the deuterium results, the carbon isotopic ratios were found to be constant from one fragment to the next of a given particle. As is the case with meteorites, the hydrogen and carbon isotopic effects appear to be decoupled.

Measurements of Mg and Si isotopes in three particles by Zinner et al. (1984) showed no deviation from terrestrial values.

Earlier measurements of the isotopic and elemental composition of the noble gases Ne and Ar in an ensemble of 13 particles by Hudson et al. (1981) indicate the presence of a solar-like component, presumably solar wind ions implanted into the particles during their recent sojourn in space as small particles. However, the presence of an indigenous trapped noble gas component of distinctive isotopic composition is also possible. Limited data on Xe isotopes indeed suggest the presence of a sizable trapped component.

Particles that fall into distinctive infrared spectral categories are currently being measured for their isotopic signatures. The data are as yet fragmentary, and no general conclusions can be drawn. Some particles falling in the layer-lattice silicate and pyroxene infrared classes have large delD values; however this is not true of all particles in these spectral categories, some of which have delD values which fall in the range of terrestrial values. At least one particle in the olivine spectral class, which is demonstrably extraterrestrial because it contains solar flare nuclear particle tracks, has a D/H ratio that is terrestrial.

The excess deuterium signature is thus highly variable in IDPs. This is similar to the situation in meteorites. Most carbonaceous meteorites do not give D/H anomalies when bulk samples are measured, but some do. In addition, acid residues of carbonaceous chondrites generally exhibit large, but variable, D excesses (e.g., Yang and Epstein (1983)). Thus in both IDP's and meteorites there appears to be a trace carrier which is highly enriched in deuterium and is present in highly variable amounts. Since the measured D

values give only lower limits on the deuterium concentration in the trace carrier phase, the D/H ratio in the carrier will be very large. A commonly held view is that these deuterium enrichments were probably caused by ion-molecule reactions in interstellar clouds.

The Collection of Interplanetary Dust by Orbiting Spacecraft

A new way to study interplanetary dust became possible with the return to Earth of parts of the Solar Maximum satellite in April 1984. The Solar Maximum parts had been exposed to the space environment for about 50 months. Impact craters on these parts are being examined by scanning electron microscopy in conjunction with energy dispersive x-ray spectroscopy; this provides an excellent means of determining the compositions of impacted particles (Kessler et al., 1985). The results show that some of the impacted materials include residues of chondritic and iron-sulfide micrometeoroids (Schramm et al., 1985).

Several dust experiments are included in the payload of the Long Duration Exposure Facility (LDEF I), whose return to Earth, originally scheduled for March 1985, has been delayed. The experiments are designed to measure the elemental and isotopic composition of dust particles. The high impact velocity of the dust makes it unlikely that unaltered material will be studied. Instead, atoms from dust impacts will be collected and analyzed. This mission is a precursor to Flyby-Comet-Coma-Sample-Return missions, and to future experiments in which the orbital parameters of individual dust particles will be determined prior to their analysis.

COMETS

Dust Particles

Our knowledge of the physical properties of cometary grains derives mostly from measurements of their thermal emission and optical scattering in comets observed within 2 AU of the sun. From these data we can make only very general statements about the grain size and composition.

The scattered light is different in color for different comets, ranging from neutral to somewhat red in the wavelength range 0.25 - 2 microns. The lack of Rayleigh scattering tells us that the optically important grains have size >=1 micron (A'Hearn, 1982). Thermal emission spectra indicate temperatures up to 25% higher than a theoretical black body in equilibrium, indicating that the grains contain absorbing material and are mostly <=10 microns in size. A size distribution for the flux of grains released from the nucleus that peaks at radii of 0.35-0.6 microns and decreases proportional to $r^{-4.2}$ for larger particle sizes is compatible with both the photometric data and analyses of the grain dynamics (Hanner, 1983, 1985).

The ratio of the scattered/thermal radiation indicates that the grains are very dark, with a geometric albedo typically 0.03-0.04 at wavelengths of 1-2 microns. The grains shed by Comet Cromelin at 1 AU were even blacker, with geometric albedo 0.015 at 1.2 microns and 0.022 at 2.2 microns (Hanner *et al.*, 1985).

Cometary emission features near 10 microns and 18 microns are generally interpreted as signifying the presence of small (<10 microns) silicate grains. The only spectral scan that has been made of the 10 micron feature (comet Kohoutek at 0.3 AU; Merrill, 1974) shows a broad structureless feature, suggesting amorphous, rather than crystalline grains.

Volatiles

Much of the icy material in comets may have arrived there from the interstellar medium as mantles on refractory grains, and therefore should be considered in this Section. Nearly all species directly measurable in comets are products of photodissociation or other processing (gas phase chemistry, ionization, etc.). In a few cases the parent molecule is reliably known, but in most cases it is not.

The dominant volatile species in the nucleus is H_2O. It was detected directly (*via* a radio emission line) in comet IRAS-Araki-Alcock 1983d (Altenhoff *et al.*, 1983), and probably detected in comet Bradfield 1974B

(Jackson et al., 1976). It is reliably inferred in other comets from the relative abundances of O, H, OH, and H_2O^+ (Weaver et al., 1981). In most comets H_2O represents more than 95% of the volatiles, although in a few comets (e.g., comet West 1976 VI) there may be roughly 30% CO or possibly CO_2 (Delsemme, 1982). CO has been detected directly in comet West by its ultraviolet emission bands (Feldman, 1982).

Other species which may reside in the nucleus and which have been directly detected include: NH_3, a trace species seen only in comet IRAS-Araki-Alcock (Altenhoff et al., 1983); HCN and CH_3CN, trace species detected in comet Kohoutek 1973f and comet 1983d, and inferred in many other comets from the presence of CN; S_2, measured in comet 1983d (A'Hearn et al., 1983), whose spatial distribution suggests that it comes from the nucleus despite the unlikely chemical situation necessary. Modeling of the chemistry in cometary comae has shown that the ices of the nucleus can not produce the observed radicals in the coma in the right amounts if the ices are equilibrium condensates, but can produce them all in the right amounts if the ices contain the complete suite of molecules seen in interstellar clouds (Mitchell et al., 1981).

The inventory of atoms in the cometary volatiles is not complete, but it seems clear that C is depleted by a factor of 2-4 relative to its cosmic abundance (normalizing to N, O, S, and Si); the abundance of H is no more than twice O (Delsemme, 1982).

Several arguments suggest that the volatiles are directly associated with the grains in the coma, and therefore presumably with the grains while they were in the nucleus. First, the reflection spectrum of the grains has shown an absorption at 3 microns in two comets: Bowell 1980b (Campins et al., 1983), and Cernis 1983l (Hanner, 1984). Both of these comets were observed far from the sun (more than 3 AU), and a suitable spectrum resolving the absorption has not yet been obtained for any comet, but the data are strongly suggestive of water ice on the grains. A second, closely related point is that comet Bowell also exhibited a remarkably high production of OH at 4 AU from the sun (A'Hearn et al., 1984), a production that cannot be explained by

vaporization directly from the nucleus, and which therefore implies that the ice is spread over the surface of all the grains in the coma. Third, a number of authors have argued that the spatial profiles of the reflected continuum in cometary spectra can only be explained if the grains decrease in size as they move away from the nucleus; this reduction in size is more easily understood if icy mantles are vaporizing. Unfortunately these observations are very difficult, and some investigators find the evidence less than convincing. Although the observations provide no evidence for a present-day connection between volatile ices and refractory grains, A'Hearn and Feldman (1985) have argued that the presence of S_2 in comets can only be explained if it was formed by the irradiation of icy mantles of interstellar grains which were incorporated in comets without significant warming. This conclusion has often been reached using less direct arguments by Greenberg (1982).

Isotopic ratios have been measured for only two volatile species in comets, both spectroscopically. $^{12}C/^{13}C$ in C_2 is >100 (average of 5 comets); but the errors are so large that this is not significantly different from the terrestrial value (see reference in A'Hearn, 1982). Upper limits for D/H in OH have been determined for several comets. In the best determined cases, the upper limit is D/H $<2\times10^{-3}$ (A'Hearn et al., 1985). The models for chemical fractionation between HDO and H_2O during condensation on grains are not yet reliable enough to determine whether these upper limits are more consistent with interstellar or presolar conditions.

CHONDRITIC METEORITES

The most primitive surviving samples of nonvolatile planetary material are the subset of meteorites called chondrites. The bulk compositions of chondrites (except for a few highly volatile elements) differ only minimally from our best estimates of the solar elemental abundances. Chondrites are aggregations of small objects (chondrules; Ca,Al-rich inclusions, or CAI's; dust particles, aggregations of which are referred to as matrix and which are discussed below) that are widely understood to have been dispersed in the protosolar nebula at the time when the solar system was formed. These objects have not been perfectly preserved since the nebular era, however. Their min-

eralogy and petrography reveal that they have actually experienced significant thermal processing, in the case of carbonaceous chondrites in a watery environment, while they resided in asteroid-sized parent bodies (Dodd, 1981; Kerridge and Bunch, 1979; McSween, 1979). Truly pristine material is rare.

The least-altered classes of chondrites are the "unequilibrated ordinary chondrites" (UOC's; evidence of slight anhydrous metamorphism; Dodd et al., 1967), C3 carbonaceous chondrites (Allende is a prominent example; possible slight anhydrous metamorphism; Clarke et al., 1970), and C2 carbonaceous chondrites (hydrous metamorphism; Fuchs et al., 1973).

Several events in the early history of chondritic material have been reliably dated radiometrically. Thus, the crystallization of several lithic components in carbonaceous chondrites, including some produced by aqueous activity on the parent body, occurred 4.55×10^9 years ago (e.g., Tatsumoto et al., 1976; Macdougall et al., 1984), and final compaction of the particulate components apparently took place during the interval from 4.5 to 4.2×10^9 years ago (Macdougall and Kothari, 1976).

Components of chondritic meteorites: chondrules

Chondrules (Fig. 2) are mm-size, more or less spheroidal igneous objects that are very abundant (up to 70%) in chondrites. It seems clear that they were once molten droplets dispersed in the nebula. Some early high-energy process melted a previous generation of dispersed solid material, which may (Wood, 1984) or may not (Grossman and Wasson, 1983) have been presolar interstellar dust. If the precursor was interstellar dust, its properties have been almost completely obliterated by the melting event that created the chondrules. Isotopic anomalies which may be a memory of presolar conditions are largely lacking--only oxygen isotope anomalies have been documented (Clayton et al., 1983).

Ca,Al-rich inclusions

This class of mm- to cm-size objects (Fig. 3) attracted scientific attention initially because they match closely in chemical and mineralogical composition the thermodynamically predicted composition of high-temperature condensates from a cooling gas of solar composition. They have been regarded by many as the most primitive objects in the solar system, and hence are thought to contain the best preserved record of early solar system processes and raw materials. However, recent studies of isotopic fractionation of moderately refractory elements in CAI's (silicon, magnesium and calcium) show that the enrichment of non-volatile elements in the inclusions is due predominantly to extensive evaporation of volatile elements from pre-existing solids, rather than to condensation of refractory elements from a gas. Furthermore, the complicated interrelationships among these elements indicate multiple events of evaporation and condensation. These events must have taken place while ^{26}Al ($t_{1/2}$, 0.7×10^{6} yr) was still alive in the solar system, as the abundance of its daughter, ^{26}Mg, has been found to correlate with the abundance of the stable isotope of aluminum (^{27}Al) among the minerals of some CAI's. In some cases, this extensive chemical processing may have obliterated earlier isotopic heterogeneities. In other cases, such as the FUN inclusions, they may reveal heterogeneities that previously existed in different chemical forms. The CAI's provide some remarkable information about the nucleosynthetic history of matter in one part of the solar system, but they should not be regarded as typical or especially primitive in comparison to other meteoritic material.

CAI's are abundant in the C3 carbonaceous chondrites, are less abundant in C2 carbonaceous chondrites, and are present, but rare, in unequilibrated ordinary chondrites. In all cases they are less abundant than chondrules. Because of the ready availability of large quantities of the Allende (CV3) meteorite, most chemical and isotopic studies of CAI's have been done in this meteorite.

Matrix

Chondritic matrix is an aggregation of dust particles of roughly micron dimension. The mineralogy and state of oxidation of matrix indicate a lower temperature of formation than that of chondrules and CAI's. If presolar interstellar grains are preserved in chondrites at all, they are located in the matrix. To date no particular class of matrix particles has been identified as presolar grains, though as will be seen, acid residues--the products of extensive laboratory processing and dissolution of bulk matrix samples--have isotopic signatures that appear to have been preserved from presolar times. The great bulk of chondritic matrix grains differ in significant ways from interstellar dust particles (Brownlee et al., 1977).

The matrices of UOC (Huss et al., 1981) and CV3 (Peck, 1983) chondrites are largely anhydrous, and in many cases consist of autonomous mineral grains (Fig. 4) that appear not to have been seriously disturbed by metamorphism. It is likely that most of these grains are condensates from the solar nebula. Some are undoubtedly the debris of comminuted chondrules and CAI's; and as noted, some may be presolar interstellar grains. C2 matrices consist largely of hydrous magnesium silicate minerals. In some cases there is unequivocal textural evidence that the hydrated minerals were produced in situ, by post-accretional hydrous metamorphism (Kerridge et al., 1979; Bunch and Chang, 1980). Elsewhere this cannot be established: the hydrous minerals may have existed as dispersed grains in the nebula or even in interstellar space, pre-dating the accretion of parent chondrite planetesimals.

Of particular interest are the matrices of a few UOC's, which consist of submicron graphite and magnetite grains (Scott et al., 1981a); and some chondritic regolith breccias (samples of the impact-comminuted surface layers of chondritic planetesimals, subsequently relithified) containing aggregates of the same graphite-magnetite material, which clearly were mixed into the regolith from some external source (Fig. 5; Scott et al., 1981b). Magnetite and especially graphite are uncommon meteoritic minerals, but they have figured prominently in interstellar grain models. However, no evidence has been found as yet that these grains had an interstellar origin.

Presolar Isotopic Signatures Preserved in Meteorites: H, C, N

A major fraction of the organic matter in carbonaceous chondrites is an insoluble macromolecular material which resembles terrestrial kerogen. It consists of a highly condensed aromatic backbone with minor aliphatic bridges and side-chains. This material is not isotopically homogeneous; different moieties within it are apparently characterized by significantly different $^{13}C/^{12}C$ and $^{15}N/^{14}N$ values and by very pronounced differences in D/H. Bulk samples of the insoluble fraction yield D/H values up to 5.4×10^{-4}, with values up to 7×10^{-4} being observed during stepwise extraction (Robert and Epstein, 1982). However, it is not known whether this represents the maximum D-enrichment preserved in meteoritic material, or whether even more highly enriched moieties exist within the organic matter. In either case, the meteoritic D-enrichments relative to the galactic value, 2×10^{-5}, require fractionation of a magnitude apparently only achievable by ion-molecule reactions at very low temperatures. Such low temperatures, and even greater D-enrichments, are observed in molecular clouds, suggesting that part of the meteoritic organic matter is of interstellar origin (Geiss and Reeves, 1981; Kerridge, 1983). Whether the kerogen-like material itself was formed in an interstellar cloud or whether it was produced by "diagenesis" in the early solar system of simpler molecules synthesized in interstellar clouds, is not known.

Presolar Isotopic Signatures Preserved in Meteorites: Oxygen

On earth, natural processes lead to fractionation of the three stable isotopes of oxygen due to differences in their masses. These mass-dependent processes produce a well-understood relationship between $^{17}O/^{16}O$ ratios and $^{18}O/^{16}O$ ratios. The observed isotopic patterns in meteorites do not conform to this simple relationship, and therefore require another major source of isotopic variability (Clayton, 1978). The simplest interpretation of the observations is that the solar nebula was isotopically heterogeneous, and consisted of two or more reservoirs differing in their ^{16}O abundances. A likely possibility is that this heterogeneity could be established and maintained if the two or more reservoirs were in chemically and physically different states, such as gas and solids. The observed meteoritic variability

could then be accounted for by various degrees of interaction and exchange between those reservoirs.

Oxygen isotopic heterogeneity is observed on every scale yet analyzed: from micrometers to planetary size. The range of excess or depletion in ^{16}O is at least 6%. The oxygen of the earth is not an end-member in the compositional variation, so that we have no "normal" solar system composition against which to measure absolute amounts of excess ^{16}O. Oxygen isotopic anomalies differ from isotopic anomalies in other elements in two principal ways: (1) they are present in all solar system bodies, (2) they involve very large numbers of atoms. These effects may result from the unique cosmochemistry of oxygen which allows it to form physically distinct reservoirs, and thus avoid the isotopic homogenization that has occurred for other elements.

There are no oxygen isotopic data on stratospherically collected interplanetary dust particles, since they are too small to be analyzed by existing techniques. Measurements on composite samples of deep-sea spherules suggest a relationship to C2 carbonaceous chondrites.

The ultimate origin of oxygen isotopic heterogeneities in the early solar system remains unknown. One possibility is the inheritance of presolar differences due to incomplete homogenization of the products of nucleosynthesis. The three stable isotopes of oxygen are produced in different astrophysical processes, and may be injected into the interstellar medium chemically bound in refractory solid phases. An alternative possibility is the generation of the heterogeneities within an initially homogenized solar system, either by nuclear reactions involving energetic particles from the sun or by isotope effects involving chemical reactions that do not follow the usual dependence of fractionation on isotopic mass. The latter possibility is suggested by the laboratory experiments of Thiemens and Heidenreich (1983), which showed that the conversion of O_2 to O_3 favors the molecules containing ^{17}O and ^{18}O and produce a fractionation pattern very similar to that observed in carbonaceous chondrites. The mechanism of the reaction has not yet been established.

Presolar Isotopic Signatures Preserved in Meteorites: Noble Gases

Anomalous isotopic patterns in noble gases (He, Ne, Ar, Kr, Xe) are found primarily in meteorite samples, in lunar dust, in putative Mars meteorites, and in planetary atmospheres. They have not been measurable in IDP's because the particles collected to date are not large enough or numerous enough. So as far as dust studies are concerned, one is limited primarily to samples from meteorites.

The meteoritic samples studied are not grains. Grains are too small to contain enough noble gas (perhaps 10^{-12} to 10^{-8} cm^3 STP/gm) for individual study. The materials studied are either samples (perhaps a milligram) of bulk meteorite, or other small bulk samples that are separated out of a whole meteorite. Selection techniques are, for example, hand-picking of a chondrule or inclusion, grinding and sieving into size fractions, gravimetric sorting into density fractions, or partial dissolution by various solvents. But in any case one gathers enough material, say a milligram, to have enough noble gas to measure. The wide ranges of details and sensitivities can be found only by referring to the literature (e.g., Podosek, 1978). Because of this need for a relatively large sample, it is not generally known what particular type of grain or chemical structure the gas analyzed resides in. Only by repeated careful inferences can the nature of the carrier of a noble gas anomaly within the meteorite be identified.

As an example of this situation, the dissolution of bulk Allende meteorite in acid has been shown to leave insoluble residues that are very rich in noble gases (Lewis et al., 1975). Because carbon and hydrocarbon polymers are not generally soluble in acid, it can be inferred that the carriers in these cases are either the carbonaceous matter of the carbonaceous meteorite or they are mineral carriers that are themselves insoluble in acid or are contained within and protected by carbonaceous matter. Further studies on the residues are also possible and yield useful information.

Another technique that has been found essential for noble gas studies is partial release of the gases as a function of temperature. For example, a

bulk sample is heated in a crucible for enough time to effectively outgas it at that temperature. The gas is collected and analyzed isotopically. Then the temperature is increased (typically by an increment of 100K) and the procedure repeated. In general, the isotopic composition of the gas released differs from one temperature fraction to the next. It is then possible to seek the minimum number of distinct components (i.e., basis vectors) that can describe the entire set of compositions of the different temperature fractions. The so-called three isotope diagram [N(i)/N(k) vs. N(j)/N(k), where i, j, k are isotopes of the element in question] is useful because it identifies mixtures of components.

Several physical mechanisms have been observed in space and in the laboratory that lead to isotopic fractionation of noble gases. One such effect is the strong fractionation of helium isotopes that occurs in the solar wind, which is presumably caused by hydromagnetic acceleration or deceleration processes, such as critical velocity ionization, in the solar atmosphere. Condensation, e.g., of nickel-iron from an argon plasma, has been observed to lead to mass fractionation in the occluded noble gas component (Arrhenius, 1972). The distribution of noble gas isotopes in meteorites suggests that such processes are also likely to affect condensing matter in space. Methods are needed to distinguish this type of effect from those due to cosmic ray interaction and nucleosynthetic contributions. Isotopic fractionation in noble gases under space excitation conditions has been only superficially explored experimentally, and further investigations would seem important for understanding the cosmic record.

With these general remarks one can detail the major patterns found in meteoritic noble gases that have been argued to have presolar memory.

Helium. Because it has only two isotopes, the rare one, ^{3}He, is useful primarily as an indicator of cosmic-ray irradiation. Perhaps the major question in that regard is whether the spallation reactions that produced ^{3}He (and also ^{21}Ne, another major indicator) occurred entirely within the assembled meteorite, or whether some earlier (possible presolar) irradiation is also

recorded. This is unsettled. Ray and Völk (1983) have discussed the nuclear reaction kinematics and the retention of recoiling nuclei.

Neon. Using temperature release fractions on bulk meteorites, Black (1972) identified five discrete components of neon, which he called Ne-A, -B, -C, -D, -E. Of these the most interesting is Ne-E, which is now known to be essentially pure ^{22}Ne (Eberhardt et al., 1979). Black even went so far as to suggest that Ne-E was a preserved presolar component, a view that is almost universally accepted today. The condensation of ^{22}Na in sodium minerals outside exploding stars (Clayton, 1975a) is the favored model for creating it (see the Section on Interrelationships). However, the nature and history of the Ne-E carrier from condensation to meteorite is yet to be specified, a problem that is shared by all noble gas connections to some degree.

Argon. With only three isotopes (36, 38, 40), one of which is a decay product of ^{40}K, it is not easy to seek very many meaningful connections to the presolar ISM. Overwhelmingly the most significant use of Ar has been the K-Ar dating method, which locates meteorite ages at 4.5×10^9 yr in undisturbed cases. One great surprise, still controversial, has emerged--the discovery of some samples that contain more ^{40}Ar than can have been produced by ^{40}K decay over 4.5×10^9 years (Jessberger et al., 1980). A possible connection to presolar dust is indicated, because decay in interstellar grains could carry excess ^{40}Ar into the early solar system. This effect was predicted before discovery as a general astrophysical clue to be sought (Clayton, 1975a, 1977). Jessberger's samples are K-rich minerals removed from Allende inclusions, and it must be remembered that the origin of these inclusions and their minerals is still not understood.

Krypton. The largest isotopic anomalies are found in acid-insoluble residues of Allende and other carbonaceous chondrites. But for various reasons the situation is not as clear or favorable to study as is xenon (below).

Xenon. This noble gas is blessed with nine stable isotopes, so it has rich possibilities for identifying specific processes. It is also fortunate

that meteorites are quite retentive of Xe, even though it is a noble gas. This means that surprisingly large quantities of Xe are available for study (perhaps 10^{-8} to 10^{-2} in comparison to abundances of neighboring refractory heavy elements). The largest literature exists on the special excess at ^{129}Xe resulting from the decay of ^{129}I, with halflife 17 million years. The major effort has been to try to fix a relative age scheme for meteorites by assuming that all excess ^{129}Xe has resulted from *in situ* ^{129}I decay in the meteorite. Clayton (1975b) questioned this on astrophysical grounds. The dating scheme has since been found to have some problems (Jordan, *et al.*, 1980; Crabb *et al.*, 1982), but the interpretation remains controversial. A portion of the excess ^{129}Xe may have been trapped from the beginning in interstellar grains that were never totally degassed, somewhat like the excess ^{40}Ar problem noted earlier.

Much more exciting are the clear presolar isotopic patterns that have been found in the elements generally. One of these corresponds to the s-process isotopes of Xe, and it has been found in acid-resistant carbonaceous residues (Srinivasan and Anders, 1978; Lewis *et al.*, 1979). This discovery has proven that the theoretical division of heavy-element nucleosynthesis into s and r components is more than just an intellectual convenience for mankind. *Nature has done it first*. The question is where and when. The occurrence of these nuclides in acid-insoluble residues (and only in the high-temperature fraction of those) suggests carbonaceous dust. Carbon-rich red giants (carbon stars) have observed excesses of s-process elements, so the condensation of carbon dust there seems to be implicated.

Xe-X, also called Xe-HL. Manuel *et al.*, (1972) discovered that concentrations of the heaviest (^{136}Xe, ^{134}Xe) and lightest (^{124}Xe, ^{126}Xe) isotopes of xenon are greatly enhanced in a single cryptic component in carbonaceous chondrites; they named this component "Xe-X". Lewis *et al.*, (1975) subsequently found that spinel and carbon in acid-insoluble residues serve as carriers for Xe-X. R- and p- process synthesis in supernovae most plausibly rationalizes this Xe component (see Interrelationship Section). As in the case of other presolar noble gas components, the carrier grains must have

survived intact during the nebular phase of solar system history in order for us still to be able to see the effect today.

Xe derived from ^{244}Pu. The existence of live ^{244}Pu ($t_{1/2}$, 82 myr) in some system of solid particles at some early time is attested to by the positive identification of ^{244}Pu spontaneous fission fragments in the Xe isotopes of meteorites (Alexander et al., 1971). There are possible implications for presolar (Clayton, 1975b) as well as meteoritic history (Podosek, 1978).

Presolar Isotopic Signatures Preserved in Meteorites: Involatile Elements

Most isotopic anomalies have been found only in very special samples and/or special phases. These samples (CAI's) are characterized by their refractory nature, and range in size from <1 mm to several cm (Fig. 3). So-called FUN inclusions have attracted most of the attention so far: most of the isotopic anomalies of involatile elements have been found in these objects. It should be pointed out, however, that small individual mineral grains which are not portions of larger inclusions could very well also be carriers of isotopic anomalies; they simply have not been studied yet to any extent. Three types of isotopic effects are observed in meteorites:

1. Radiogenic effects seen as enrichment of the daughter nuclide. Examples are ^{26}Mg excesses from ^{26}Al, ^{107}Ag from ^{107}Pd, and ^{142}Nd and ^{143}Nd from ^{146}Sm and ^{147}Sm. Radiogenic effects can be large for large parent/daughter concentration ratios (e.g., ^{26}Mg excesses of >100% in Dhajala hibonite for ^{27}Al/^{24}Mg of 17,000: Hinton and Bischoff, 1984).

2. Mass-dependent fractionation (the F in FUN). Usually up to 1-2%/amu.

3. Non-mass-dependent excesses or deficits of certain nuclides, of unknown origin (the UN in FUN).

Both F and UN anomalies are present in FUN inclusions. These samples are exceedingly rare; only a few have been found so far, but most of the experimental work has been concentrated on them.

The topic of isotopic anomalies is too complex to be covered adequately in the brief survey that follows. For more details the reader is referred to reviews by Clayton (1978), Begemann (1980), Lee (1979), and Wasserburg and Papanastassiou (1982). Isotopic anomalies have been found in the following elements:

Mg--FUN anomalies in FUN inclusions; in Murchison hibonite, only F with no accompanying UN effects (Hutcheon et al., 1983), and an excess of ^{26}Mg from the decay of ^{26}Al.

Si--FUN anomalies in FUN inclusions. F effects in Mg and Si are related to fractionation effects in O isotopes.

Ca--FUN anomalies in FUN inclusions; also ^{48}Ca excess, fairly common but small in non-FUN CAI's (Jungck et al., 1984).

Ti--FUN anomalies in FUN inclusions (Niederer et al., 1985), but also the ubiquitous presence of complicated UN anomalies in many carbonaceous chondrites; ^{50}Ti excess of up to 10% in C2 hibonites (Fahey et al., 1985).

Cr--^{54}Cr excess in Allende CAI's (Birk and Allegre, 1984); probably related to ^{50}Ti.

Sr, Ba, Nd, Sm--UN anomalies in FUN inclusions.

Ag--^{107}Ag excess from the decay of ^{107}Pd.

These isotopic anomalies are mainly restricted to carbonaceous chondrites. Exceptions are radiogenic ^{107}Ag in iron meteorites (Kaiser et al., 1980), and ^{26}Mg anomalies in ordinary chondrites (Hinton and Bischoff, 1984).

Isotopic anomalies in meteorites have been taken by many to be signatures of presolar material which survived the homogenization process of the formation of the solar system. What evidence is there that any IS dust material survived? It is clear that _some_ isotopic anomalies must have been produced outside of the solar system, and prior to its formation. There is strong evidence that live ^{26}Al was present at the time of the formation of the minerals in which ^{26}Mg excesses are now found. Fractionation effects could be the result of solar system processes. Indeed, _some_ F effects are correlated with the thermal histories of the specimens. For example, fine-grained (Group II) condensates are consistently enriched in lighter Mg and Si isotopes, while coarse-grained (Group I) evaporative residues are enriched in the heavy isotopes. Recent laboratory experiments which produced non-linear mass fractionation effects in Mg by thermal evaporation (Esat _et al._, 1985) make it appear possible that the small Mg and Si UN anomalies seen in FUN inclusions are the result of solar system processes.

However, there is no doubt that a variety of isotopic anomalies must be of nucleosynthetic origin. This is the case for most Ti anomalies, especially the very large ^{50}Ti excesses; also for ^{48}Ca and ^{54}Cr anomalies, which probably have the same source. It is also the case for the elements Ba, Nd, and Sm, where definite r-process or s-process patterns have been observed.

It is not generally understood why many of these nucleosynthetic anomalies are seen in FUN samples, _i.e._, why they are associated with mass-dependent fractionation effects. There are notable exceptions to this association of F with UN:

1. Titanium isotope anomalies, which were originally found in FUN samples, are also ubiquitous in other samples which do not show any mass fractionation nor any isotopic anomalies in other elements. Most prominent is the 10% ^{50}Ti excess in Murray hibonite (Fahey _et al._, 1985) which does not show a Mg anomaly. The anomalous Ti has a homogeneous distribution in this 40 micron mineral grain.

2. Very large F effects, without other anomalies, have been found in a Murchison hibonite by Hutcheon _et al._ (1983). The mean Mg fractionation is +10%/amu, but the anomalous Mg is heterogeneously distributed in tiny patches, among which the fractionation ranges up to >35%/amu.

The Hutcheon _et al._ (1983) ion microprobe study is the only one that points to small carrier grains, and thus possibly to preserved IS dust. The only problem is that, unlike a clear nucleosynthetic signature, a manifestation of mass-dependent fractionation is no definite proof of a presolar origin. Most techniques of isotopic analysis do not allow the determination of the spatial distribution of isotopic anomalies in individual mineral grains. Normally, the large sample size and the chemical processing necessary for analysis destroys this information. In cases where the spatial distribution can be measured (by ion probe), no heterogeneous distribution of isotopic anomalies on a micron size scale has been found except for the above example.

Most meteoritic matter is considerably coarser-grained than IS dust, and has undergone thermal processing 4.5×10^9 years ago. Thus it is likely that most properties of the IS dust precursor to meteorites have been erased. No direct, unequivocal experimental evidence exists for the existence of IS dust grains in meteoritic material. Consequently, any isotopic anomalies of presolar (nucleosynthetic) origin that were brought into the solar system were incorporated into larger objects (individual larger mineral grains, whole CAI's) from IS dust grains during the early stages of the solar system, and at this point the dust grains lost their identity; or possibly these larger objects themselves were of presolar origin. While this is unlikely (_e.g._, why would extreme ^{50}Ti effects be found in a hibonite with normal Mg isotopic composition?) and probably is not the case for whole CAI's, it cannot be strictly ruled out for some individual mineral grains. Only improved measurements probing the isotopic composition on a small spatial scale will be able to settle this question.

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Figure Captions

Figure 1. An interplanetary dust particle (IDP) collected in the earth's stratosphere; note 1 micron scale bar. This particular object is a chondritic porous aggregate (CPA), consisting of relatively large grains of crystalline Mg,Fe silicates and smaller (0.1 micron) anhydrous grains of variable composition. Figure from Bradley et al. (1983b).

Figure 2. Chondrules in the Tieschitz UOC chondrite (thin section, illuminated by transmitted light; width of field, 4 mm). These consist largely of the Mg,Fe silicates olivine and pyroxene. Their textures (crystal morphologies) are characteristic of igneous rocks. Figure from Wood (1985).

Figure 3. A large (diameter, 2.4 cm), coarse-grained Ca,Al-rich inclusion (CAI) from the CV3 chondrite Allende. Thin section, illuminated by transmitted light. The minerals are melilite, anorthite, fassaite, and spinel, compounds enriched in the most involatile elements (such as Ca and Al). The igneous texture and spheroidal shape make it clear that this object was once a molten globule. Figure from Clarke et al. (1970).

Figure 4. Matrix in the CV3 chondrite Allende (SEM backscattered-electron image of a polished section; width of field, 110 microns). This consists of a loose aggregation of, mostly, plates of ferrous olivine which appear as rods where cut by the section. Also visible are minor amounts of metal and sulfide minerals (white) and pyroxene (darker gray, irregular). Pore space appears black. Figure courtesy of J. A. Peck.

Figure 5. Submicron graphite-magnetite aggregate in a clast from the regolith breccia chondrite Sharps (SEM backscattered-electron image of a polished section; note 5 micron scale bar). The finest-grained areas of the image, which are poorly resolved, are graphite and magnetite. White, irregular grains are metal and sulfide minerals. Figure courtesy of S. Recca and E. R. D. Scott.


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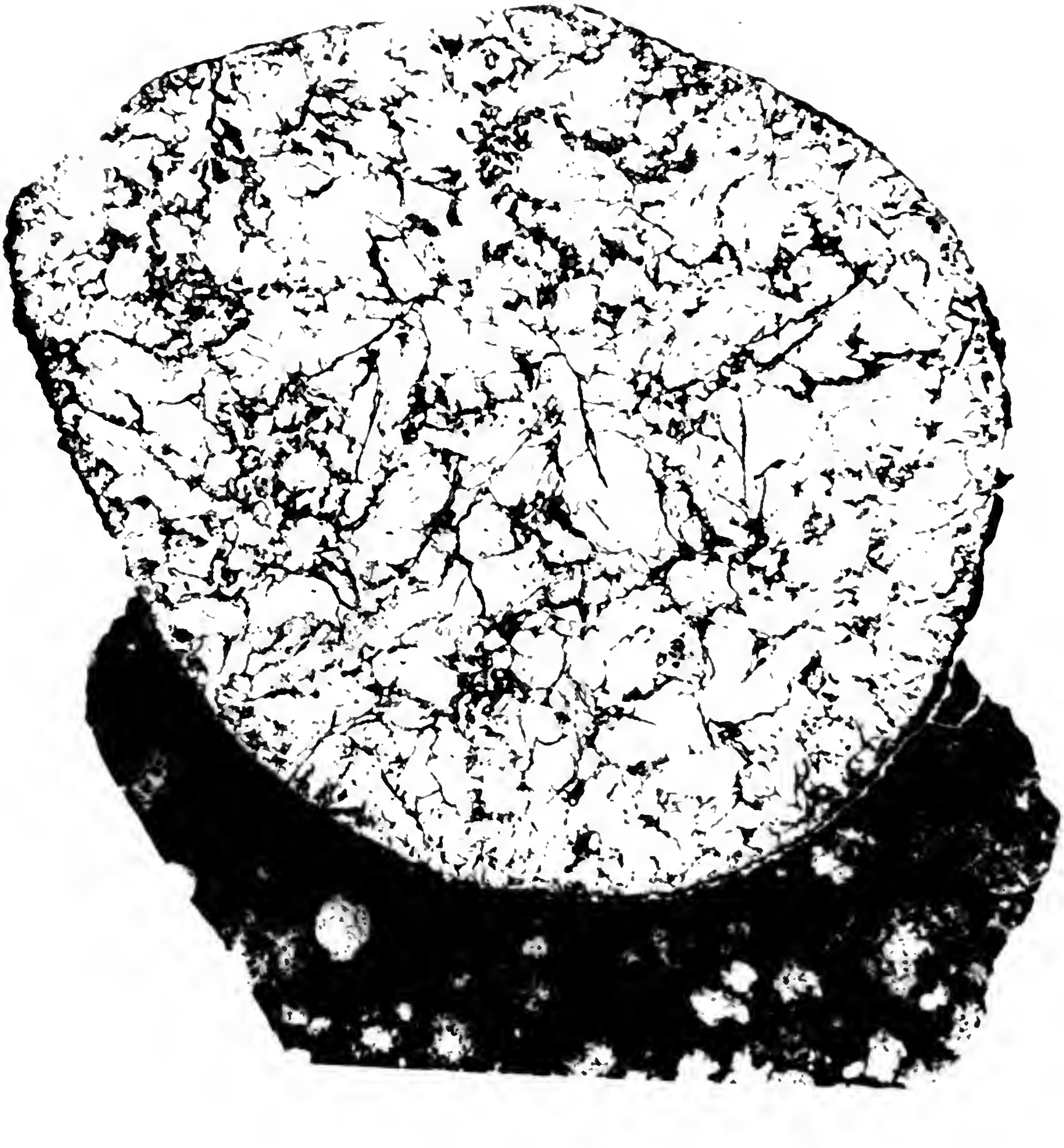

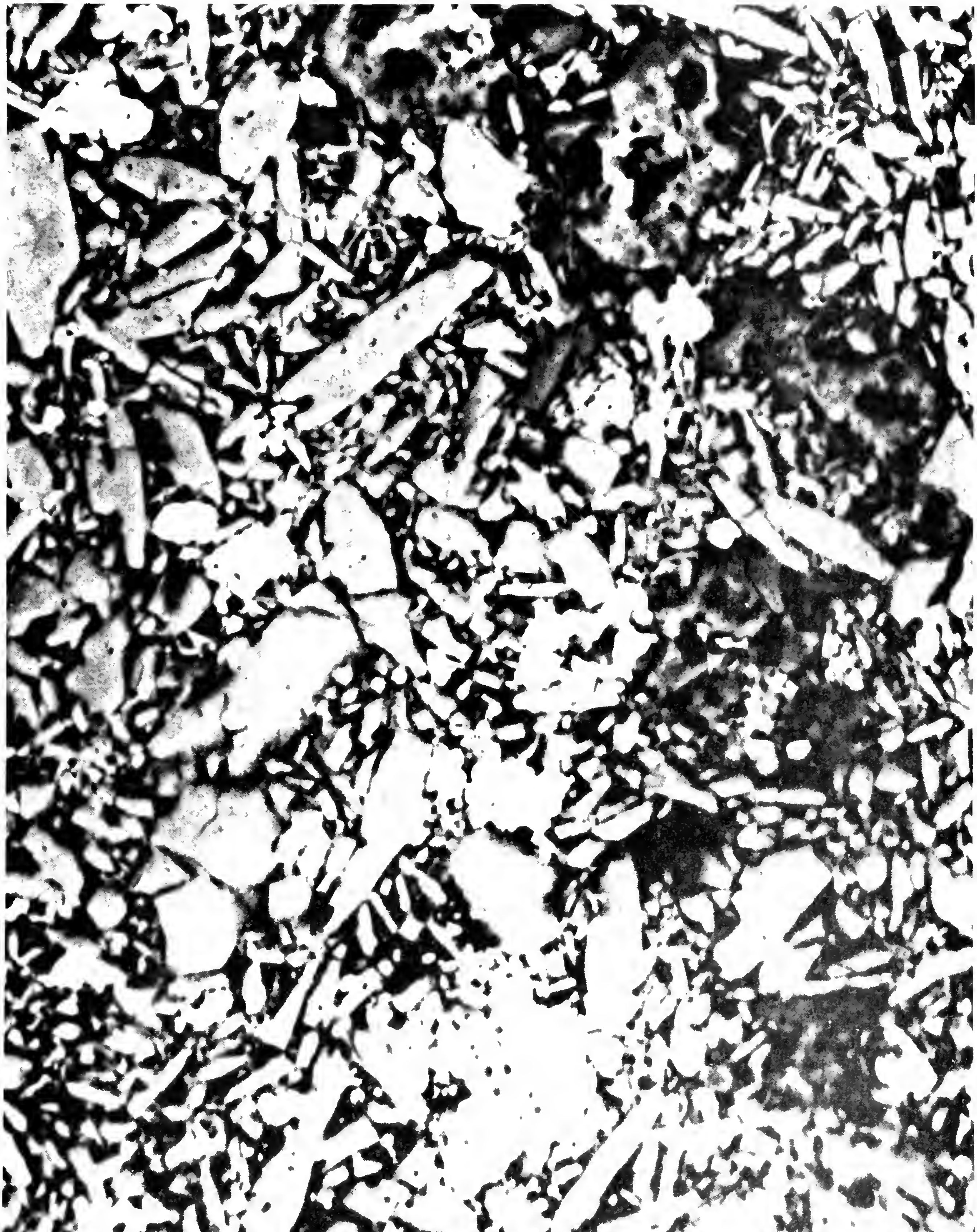

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WORKING GROUP ON CIRCUMSTELLAR/INTERSTELLAR RELATIONSHIPS

A. E. Glassgold et al.

Stars of various types are believed to be the main source of IS dust grains. The most important confirmed source is evolved giant and super giant stars, which are estimated to eject mass at a rate of approximately $0.3M_{sun}$ per year (Knapp and Morris, 1985) with a gas to dust ratio on the order of 100 (Knapp, 1985). Supernovae may also contribute a mass loss rate of the same order of magnitude with important additions of heavy elements to the grains. In reviewing the differences between circumstellar (CS) and interstellar (IS) dust the working group discussed the following topics:

1. Alteration of CS Dust Grains on Entering the ISM - Before a grain begins its long and complicated life in the interstellar medium, it may undergo significant changes as the CS ejecta dissipate and merge into the ISM. Although practically no work has been done on this subject, it was noted that a terminating shock, occurring when a CS envelope (CSE) is stopped by the ISM, may alter the grains. Another concern is with the high speeds of supernovae ejecta, which could lead to significant grain destruction.

2. Size Distributions of CS and IS Grains - Much less is known about the size distribution of CS as compared to IS grains. Jura (invited talk) presented evidence for the rough similarity in size of IS and CS dust grains around evolved stars. One approach might be to combine UV absorption measurements with observations of near infrared emission features, as Sitko, Savage, and Meade (1981) have done for early type stars.

Observations of CS dust envelopes at high spatial resolution might also be useful in this connection. Fairly sophisticated theoretical models can be constructed for symmetrical envelopes which can be used to interpret observations of scattering (at optical wavelengths) and emission (at IR wavelengths). The models provide a diagnostic aid for determining the gross properties of the CS grain size distribution. The spectral shape of the 9.7 micron feature might also give a clue to the amount of processing which CS grains undergo

before entering the ISM. For example, the grains might become crystalline if they are annealed in the CS outflow.

3. Space Observations of CS and IS Dust - Observations from space can advance our understanding of circumstellar grains and their role in mass loss from stars. For example, grains flowing out of stars scatter the incident starlight, producing reflection nebulae, and re-radiate the stellar radiation in the infrared. A reflection nebula can be seen in the case of the Egg Nebula (CRL 2688) where bipolar outflow is observed edge on. However, in most cases (e.g. Alpha Orionis) it is difficult to observe the reflection nebulae because of scattering in the Earth's atmosphere. With Space Telescope, it should be possible to make maps of CS reflection nebulae at various wavelengths in the optical and ultraviolet bands.

More complete information on the CS grains can be obtained from studies of the energy balance of the nebulae, which can be accomplished by measuring the flux of radiation in the IR. SIRTF will be suitable for measuring the dust re-radiation from 100 to 200 microns and, in some cases such as Alpha Orionis, will also be able to provide maps of the emission.

It should be noted that the proposed Far Ultraviolet Spectroscopic Explorer (FUSE) could also contribute to the study of interstellar grains. The principal instrument will be a spectrograph optimized for the 912 to 1200A band. Although its high resolving power (30,000) is intended for abundance determinations of the interstellar gas, lower resolutions will be available for determining UV extinction curves. Spectrographs will also be available in the 200 to 912A and 1200-2000A bands, and the latter instrument would also be useful for extinction measurements.

4. Comparison of CS and IS Spectra - A detailed understanding of the quantitative differences observed in CS and IS dust spectra would be most informative on the properties of newly formed dust and how it is modified in outflows and in the ISM. We divide the following discussion of comparisons according to whether the CSE is C-rich or O-rich.

a. O-Rich CSEs - The 9.7 micron silicate feature is observed in both CS and IS environments. Although the CS emission feature is qualitatively similar to that observed toward the Orion Trapezium region, there are significant quantitative variations from star to star (Forrest et al., 1975). These differences could have a variety of explanations, e.g. size, composition, and physical conditions. Papoular and Pegourie (1983) have emphasized the importance of the size distribution, but members of the workshop suspect compositional differences play a role. In discussing these interesting quantitative details, it is important not to forget that the similarity between the IS and CS 9.7 micron features (usually associated with the Si-O stretch mode), supported by a similar correspondance between the 20 micron feature (usually associated with the O-Si-O bending mode) provide support for a connection between IS and CS grains.

The shape and position of the 9.7 micron absorption feature can also vary from IS cloud to IS cloud. Aitken et al. (1981) have made high spatial resolution observations of the Orion sources, BN, IRc2, and IRc4, which suggest that the differences between these sources are most likely due to radiative transfer effects, rather than composition.

b. C-Rich Stars - The IR spectra are generally fairly smooth (Forrest et al., 1975), and are believed to arise from thermal radiation by amorphous carbon grains. A feature at 11 microns is commonly ascribed to SiC.

The most important IS dust spectral feature, almost always associated with carbon (in the form of graphite), is the bump in the selective extinction at 2175A. This bump has not been detected in the CSEs of evolved C-rich stars, which produce a large part of the IS dust, because the stars are not sufficiently bright in the UV. The feature has been seen in NGC 7027, but it is uncertain whether it is CS or IS. R Corona Borealis does show an extinction peak near 2400-2600A (Hecht et al., 1984), which is believed to indicate amorphous or glassy carbon. Wu et al. (1978) observed a 2200A bump in a C-rich nova, Nova Cygni 1978, but a quantitative measurement is difficult because of the varying continuum. The 2175A bump has also been detected in some A,B (Herbig Ae,Be and peculiar shell) stars (Sitko et al., 1981), some

what weakened and shifted in wavelength - presumably due to the special physical environments of these stars.

Russell et al. (1978) have detected strong emission at 6.2 and 7.7 microns in HD 44179, the central star of the Red Rectangle. This object also has emission features at 3.3 and 11.3 microns, as well as an unusual UV spectrum (Sitko et al., 1981). The IR emission features are also observed in NGC 7027 and other sources where UV radiation is present. They are now believed to arise from PAHS, as discussed in Jura's review. Although the evolutionary state and physical properties of HD 44179 are quite obscure, the observations do suggest a particularly interesting connection between IS and CS dust. It would clearly be of great interest to detect PAHS in CS environments where dust is forming.

5. Isotopic Signatures of IS Dust - One potential way to connect CS grains and/or large molecules and interstellar material is to measure isotope ratios in the IR bands. For example, the 3.4 micron absorption band, seen toward the galactic center, has structure appropriate for aliphatic hydrocarbons. It may be hoped that as signal-to-noise and sensitivity improve the ^{13}C counterpart will be measured. Carbon stars seem to have a characteristic ratio of ^{12}C to ^{13}C of about 35. It would also be of interest to search for the deuterated C-H stretch which should be observable at about 4.76 microns.

6. Magellanic Clouds and Nearby Galaxies - Studies of dust in nearby galaxies are important in understanding the dust in the Milky Way. Further progress should be possible with Space Telescope. It is interesting to note that the heavy elements in the Magellenic clouds are significantly reduced relative to the Milky Way, and that the C/O ratio is larger (Dufour et al., 1982). Jura (1985) has suggested an explanation of this situation in terms of ideas about mass loss from red giants and stellar evolution. If the final stages of mass loss from evolved stars are driven by radiation pressure on grains, then the Magellenic Cloud stars have lost relatively less mass in the past thereby producing a larger number of supernovae - which could explain the larger O/C ratio. The observation of so many C stars in the clouds would then suggest that this situation is now being altered by the injection of C-rich

material, and that the trend of chemical evolution of the clouds is toward the chemical composition of the Milky Way. Although this scenario is speculative, it does illustrate how the study of abundances and dust in nearby galaxies is relevant to our understanding of galactic chemical evolution.

7. The Life Cycle of Dust Grains - The preliminary theoretical result of Seab and collaborators (this volume) that most IS grains will be destroyed in about 100 million years was one of the most interesting results discussed at the workshop. Seab et al. attempt to follow grains in their passage through the different phases of the ISM, treating various growth and destruction processes. The effects of fast ($\geq$100 km/s) shocks are found to be most important; such shocks are believed capable of completely evaporating grains. The complete model involves many complex physical processes some of which are not completely understood. Seab's result requires a dust replenishment time between 10^8 and 10^9 years, i.e. grains must be formed in the ISM - and it is quite unclear how this can be accomplished. The situation could be saved by modifications in the theory, e.g. some fraction of the available supernova energy may be lost into the halo of the Milky Way, or grains may be shattered by fast shocks rather than vaporized. In any case, the processes which determine the life cycle of dust grains need to be better understood before this important question can be resolved.

8. Physical and Chemical Data - The discussion of grain properties, particularly spectral features (exemplified by the recently recognized importance of polycyclic aromatic hydrocarbons) highlights the importance of basic physical and chemical information. Further progress in understanding the nature of CS and IS dust and their gaseous environments requires additional spectroscopic data on a wide variety of condensed materials and on the radiative properties of individual molecules in many wavelength bands. This is a common situation for research on the interstellar medium, and the normal activity of physicists and chemists never seems to satisfy the demands of astrophysics. This working group would like to encourage NASA support for some of the most basic research in this area to permit increased realization of the potential of space based research. Scientists interested in CS/IS/IP dust

could also make an important contribution by encouraging their home institution to promote basic research in related areas of physics and chemistry.

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INTERRELATIONSHIPS BETWEEN INTERSTELLAR AND INTERPLANETARY GRAINS

D. D. Clayton et al.

INTRODUCTORY REMARKS

No relationship between solar system "dust" (SSD) and interstellar dust particles (ISMD) can be taken for granted. The historical position has, for the most part, been that little or no relationship exists -- that SSD and meteorites come from collisions among bodies formed in the solar system from dust also formed from an initially gaseous solar nebula. Today that position is being rethought, spurred primarily by the discovery of isotopic anomalies in meteorites. It is unclear whether SSD has any relationship to the ISM or not. Our purpose then is to seek evidence for the extent of any existing relationships.

What one wants is a complete description of interstellar grains so that comparisons with well documented solar-system samples can lead by inference to the history that has produced the latter from the former. This is a lot to ask, but slowly the information can be assembled. Are interstellar grains chemically fractionated (e.g. Si separated from Fe) or are they rather well mixed, of roughly chondritic abundances? Do core-mantle structures record fractionation owing to thermal condensation sequences or are grains more amorphous? What is the composition and history of volatile mantles? What special isotopic components exist? For studies related to the origin of the solar system one may need to know the specific composition in molecular clouds, whereas for grains entering the solar system today one may require the properties of grains in a hot low-density shocked medium like that surrounding the solar system. To maintain some structure we will distinguish between these two major epochs that are under study.

I. INTERRELATIONSHIPS AT TIME OF SOLAR FORMATION

A. Meteoritic Record

Radioactive chronometers show that the meteorites assembled about 4.55 x 10^9 years ago, probably in association with the birth of the sun. Until about ten years ago, most meteoriticists assumed that the dust contained within the meteorites also had formed at that same time from an initially gaseous solar system. Following the discovery of isotopic anomalies there developed a view (Clayton, (1978) Moon and Planets, 19, 109) that severe isotopic and chemical fractionation of specific subclasses of presolar dust from others has left many "fingerprints" in the meteoritic record. This perspective succeeds the view of a nearby supernova admixing isotopic anomalies inhomogenously into the solar gas (Cameron and Truran (1977) Icarus, 30, 447 and most papers reporting isotopic anomalies). These "fingerprints" partially survived the chemical processes of transformation from submicron material to macroscopic minerals and breccias, leaving a chemical memory of their prior state that needs "developing" (as in film) by careful chemical experiments. To the extent that this interrelationship exists, it records conditions at that time rather than today, even though the chemical experiments are done today. The implied relationship is between interstellar dust and the processes of aggregation and chemical alteration that occurred within the forming solar system, probably in a turbulent accretion disk around the forming sun (Morfill and Volk (1984) Astrophys. J., 287, 371: Cameron (1978) Moon and Planets, 18, 5; Lin (1981) Astrophys. J., 246, 972). In this general theory of the meteoritic record, one does not expect to find ISMD per se, but rather effects remembered when it is fused into new forms. The ways in which this might have happened are frontier research areas.

What one sees today (primarily from isotopic anomalies) are clues that a relationship existed 4.55 x 10^9 yr ago between ISMD and the SSD of that era which aggregated into the parent bodies of the meteorites. Conceptually one can distinguish between the relationship of SSD to ISMD and the relation of SSD to Circumstellar dust. Because the experimental evidence relating to this interrelationship is primarily chemical, the thread being sought is that of

chemical memory from source to meteorite (Clayton (1982) (Q. J.Roy. Astron. Soc. 23, 174). To clearly envision ISMD/SSD interrelations, it is first advisable to identify the more dramatic circumstellar/SSD connections, because it is they that attest to the entire cosmic chemical memory. The following circumstellar/meteoritic connections are not offered to "explain" more complicated meteoritic situations, but rather to highlight the excitement of well documented isotopic patterns that may be rationalized by nucleosynthesis and stellar condensation. This excitement was the direct result of dozens of experimental discoveries by meteoritic chemists over the past dozen years. It will not be our intent to document all of these in what follows, but rather to point to especially clear treatments.

A.1 Circumstellar/Meteoritic

Many observable chemical properties of meteorites seem to have first been established during mass loss from stars. Condensation in the outflow can freeze circumstellar material before it mixes with the ISM, freezing an anomaly while it is still quite large. Two stages of processing, one in the ISM and one in the processes of solar aggregation, will have modified these materials.

i) Isotopic Connections (Circumstellar)

Because dust is expected to condense in stellar outflows, even of supernovae (Hoyle and Wickramasinghe, 1970 Nature, 226, 62; Clayton, 1975 Nature, 257, 36) and novae (Geisel et al., 1970 Ap. J. (Letters), 161, L101; Clayton and Hoyle, 1976 Astrophys. J., 203, 490; Clayton and Wickramasinghe, 1976 Astrophys. Spa. Sci., 42, 463), isotopic structures specific to the star and even to specific radial zones of the star may be trapped within that dust and offer an explanation for the origin of many isotopically anomalous materials. Key examples of this circumstellar/meteoritic connection are:

(a) Ne-E, an almost isotopically pure ^{22}Ne component identifiable as a specific gas release from certain meteoritic samples (Black, Geochim. Cosmochim. Acta, 36, 377 (1972); Eberhardt et al., 1979 Astrophys. J. (Letters),

234, L169; Lewis et al., 1979 Astrophys. J. (Lett.), 234, 165). Clayton (1975, Nature, 257, 36) suggested that sodium condensed in nova and supernova effluent and that these grains, enriched in ^{22}Ne after condensation by ^{22}Na decay during the next several years, could carry a ^{22}Ne component in ISMD. Although no other explanation seems to produce such a high-purity sample of ^{22}Ne, it cannot be concluded merely by default that this source is the correct one. Still needed are definitive descriptions of the meteoritic carriers and the way they evolved from the circumstellar carriers.

(b) ^{16}O, a monotopic excess of up to 5% in anhydrous minerals from Allende inclusions and other related objects. In their discovery paper R. Clayton et al. (1973, Science, 182, 485) speculated that the ^{16}O-excess came from interstellar grains with a nucleosynthetic history different from average solar system material, while D. Clayton (1975, Astrophys. J., 199, 765; 1977 Icarus, 32, 255, 1978 op. cit) argued instead that condensation in the outflow of a supernova interior was necessary. Later Cameron and Truran (1977 Icarus, 30, 447) interpreted the available observations as an inhomogeneous spatial admixture of newly synthesized ^{16}O from a supernova trigger to solar birth. One current model is that the supernova condensates (SUNOCONs) created ^{16}O-rich refractory grains, thereby establishing a generic line to the refractory ^{16}O-rich meteoritic minerals. That spinel ($MgAl_2O_4$) is the most ^{16}O-enriched of all interstellar minerals is predicted by the SUNOCON theory, since that mineral is predicted to be the major condensate of the carbon-burning ejecta (Clayton 1977, Earth Planet. Sci. Lett., 35, 398; Lattimer et al., 1978 Astrophys. J., 219, 230). However, it does not follow that the spinels as found in meteorites are themselves SUNOCONs, or even that the spinel agreement is more than a coincidence; more likely the SUNOCONs were nucleation sites for growth or amalgamation of macroscopic spinels in the secondary mineralization processes occurring in the solar nebula. R. Clayton (1984 Protostars and Planets II, Tucson) has described what the meteoritic evidence seems to suggest. This theory also predicts that refractory interstellar dust must be more ^{16}O-rich in bulk than is interstellar gas, a useful feature of models of later exchange of oxygen (R. Clayton and Mayeda (1977) Geophys. Res. Lett., 4, 295; Wood, 1981 EPSL 56, 32).

(c) Xe-HL, once called "carbonaceous chondrite fission (CCF) xenon" and sometimes referred to as Xe-X. Lewis et al. (1975 Science, 190, 1251) made a great innovation by chemically separating via acid dissolution the microscopic portions of meteorites that carry this Heavy-isotope-rich and Light-isotope-rich component of anomalous xenon. The name CCF xenon has largely been discarded after Manuel et al. (1972 Nature, 240, 99) showed that the associated light-isotope excess could not be fission xenon, so that a name involving fission xenon would not seem appropriate. They suggested the name Xe-X and also suggested that a mixture of r-process xenon and p-process xenon, which bears a similarity to Xe-X, could have been ejected into the solar system by a nearby supernova. Clayton (1975, Ap. J., 199, 765; 1976 Geochim. Cosmochim. Acta, 40, 563) preferred condensation within SUNOCONs; Black (1975 Nature, 253, 417) advanced a similar interpretation. SUNOCONs greatly shortened the range of half lives of fissioning nuclei that could have contributed to a fission component. Subsequent experimental studies by Lewis et al. (Nature, 305, 767 (1983); Science, 222, 1013 (1983)) demonstrated that in situ fission, that is to say, fission within the meteorite in its present form, is no longer a viable alternative. Neither the nuclear origin nor the history of this component has been pinned down, but some involvement with circumstellar dust seems to be involved on general grounds. A promising picture is high speed implantation in circumstellar carbon grains. (Clayton (1981) Proc. Lunar Planet. Sci., 12B, 1781). In a more popular account, Lewis and Anders (Scientific American, 249, 66 (1983)) have stressed experimental evidence for the connection between this component of anomalous xenon and grains of carbon, which are presumably interstellar.

(d) Xe-s, or s-process xenon. In acid residues from the Murchison meteorite, Srinivasan and Anders (1978, Science, 201, 51; Lewis et al., 1979 op.cit.) found clear evidence of some chemical carriers that had trapped s-process xenon before it could mix with ISM gas. Condensation of carbonaceous carriers in red giant (C star, S star) atmospheres seems indicated. This possibility had previously been predicted in a paper submitted for publication in 1975 (Clayton and Ward, Astrophys. J., 224, 1000 (1978)). What Clayton and Ward (1978) argued is very simple and general: because the fractions of xenon condensing into grains could not have accidentally been identical for s-

process events and r-process events, any subsequent mechanical variations in the interstellar dust/gas ratio must be associated with corresponding s/r fractionations in the heavy isotopes of a given element. This single diagnostic should find many applications as experimental resolution continues to improve. But in the case of Xe-s, the observations could be taken even further by Swart et al. (Science, 220, 406 (1983)), who showed that it is carried in carbonaceous material having about twice as much ^{13}C as terrestrial carbon.

(e) Neodymium decomposition. In addition to clearing up some important questions for nucleosynthesis theory, the recent measurements of the neutron-capture cross sections of Nd by Mathews and Kappeler (Astrophys. J., 286, 810 (1984)) bring two relationships between Circumstellar and meteoritic dust into clearer focus. The first is a confirmation that the isotopic pattern of Nd found in acid resistant residues (therefore carried in a carbonaceous component) of the Allende meteorite measured by Lugmair et al. (1983 Lunar Planet. Sci., 14, 448) does indeed fit the s-process pattern if the sample carries the isotopic fractionation suggested by Clayton (1983 Astrophys. J. (Letters), 271, L101). If so, this Nd pattern is similar to that of s-process Xe, but it is the first s-process pattern identified in a refractory element. The neutron cross sections also confirm that the Nd pattern in the FUN Allende inclusion EK1-4-1 (McCulloch and Wasserburg, 1978 Astrophys. J. (Letters), 220, L15) appears to be a simple excess of the r-process isotopes averaged over nucleosynthesis events in the same way that bulk solar matter itself has. Identification with average r-process abundances speaks against (Clayton (1978) Astrophys. J., 224, 1007) a neighboring supernova injection and in favor of a chemical-memory fractionation of the ISM, perhaps even by gas/dust fractionation but also perhaps by r-dust/s-dust fractionation. What can be said without controversy is that continuing measurements of isotopically anomalous samples will be invaluable in the search to identify the chemical memory involved. Decomposition of Sm isotopes confirmed this same interpretation (Lugmair, Marti and Scheinin, 1978, Lunar and Planet Sci., 9, 672; Clayton, 1979 EPSL, 42, 7; Lugmair et al., 1983, Science, 222, 1015).

(f) Extinct refractory anomalies in SUNOCONs. Clayton (1975 Nature, 257, 36) argued from the theory of nucleosynthesis that refractory SUNOCONs should condense some key nuclei as short-lived progenitors. He especially singled out ^{41}K (via ^{41}Ca) and ^{44}Ca (via ^{44}Ti) as targets of study (see also 1977 EPSL, 36, 381). Although neither prediction has yet been confirmed, tantalizing hints exist in published data. A specific ^{44}Ca anomaly would be especially valuable because its progenitor is, like that of Ne-E, much too short-lived to exist in the interstellar medium or solar system, so that an incontrovertible circumstellar/interplanetary connection would be indicated. The special case of extinct ^{26}Al, predicted to compete with live ^{26}Al as a source of excess ^{26}Mg, receives special attention in the next section.

(g) Interstellar ^{26}Al and excess ^{26}Mg. When groups in Australia and Caltech (Gray and Compston, 1974 Nature, 251, 495; Lee et al., 1977 Astrophys. J. (Letters), 211, L107) first showed that aluminum-rich minerals within the Ca Al-rich inclusions (CAI's) from the Allende meteorite carried an excess of the heaviest isotope of magnesium, ^{26}Mg, it was concluded by some meteoriticists that a supernova explosion beside the forming solar system must have peppered the solar cloud with radioactive ^{26}Al. This model has been shaken by the detection of radioactive ^{26}Al in the interstellar medium today. The historic first detection of interstellar radioactivity was made by the HEAO 3 spacecraft (Mahoney et al., 1984, Astrophys. J., 286, 578) which recorded a measurable flux of 1809 keV gamma rays striking the solar system. The 1809 keV gamma rays are well known signatures given off following the beta decay of an ^{26}Al nucleus. The HEAO 3 measurements indicate that about 4.8 such gamma rays impact a square meter in the solar system every second, and come from the general direction of the center of our Galaxy. Any lingering doubts about the reality of this astonishing discovery have now been removed by a confirmation using the Solar Maximum Mission that was so dramatically repaired by the Shuttle astronauts and which carried a gamma ray spectrometer that had since February 1980 taken unintentional periodic looks at our Galactic center. That spectrometer team (Share et al., 1985, submitted to Astrophys. J.) confirms a flux of about 4.0 gamma rays per square meter per second from the general direction of the Galactic center, in direct agreement with the HEAO 3 measure-

ment. It can now be asserted without reasonable doubt that some source of radioactive ^{26}Al lies in the general direction of the galactic center.

The analysis of the magnitude of this gamma ray flux and its implications for both the origin of the elements in explosions of stars and for the origin of the Allende minerals was undertaken by Clayton (1984, Astrophys. J., 280, 144) who concluded: (1) if the ^{26}Al is spread uniformly throughout the interstellar gas, its concentration of about 10 parts per million of aluminum is rather close to the fossil evidence found in Allende minerals, suggesting that the requirement of a special supernova trigger to solar formation may have been unnecessary; (2) supernova explosions are not adequate to maintain this average level of interstellar radioactivity, so that nova explosions or gas streaming away from giant stars are the more likely origins of the radioactive aluminum. The ineffectiveness of supernovae in maintaining the observed interstellar concentration also argues against implicating a specific supernova with the solar origin. Cameron now argues (Icarus, 60, 416 (1984)) that wind from an asymptotic giant branch star of about one solar mass carried ample ^{26}Al along with it and participated hydrodynamically in the formation of a molecular cloud core wherein the sun formed. Interpretation of the excess ^{26}Mg in Allende aluminum-rich minerals depends upon the correct interpretation of the ^{26}Al gamma ray line, which requires better information on the angular distribution of the gamma rays. Because of wide viewing angles the HEAO 3 and Solar Maximum Mission teams can not be very precise about the angular distribution. Although it is "consistent with" radioactivity concentrated in the galactic plane having peak intensity near the Galactic center, the data might not require that interpretation. A single recent supernova toward the general Galactic center would occupy a large circular area on the sky; however it would be most unlikely that the center of such a nearby distribution would happen to lie in the plane of the Galaxy. If the observing teams can successfully show that the latitude distribution is narrow and centered on the plane, we will be forced to accept the interpretation that the observed ^{26}Al concentration is a general feature of the interstellar gas.

The interstellar isotopic concentration (^{26}Al/^{27}Al = 10 parts per million) lies squarely between but distinct from the concentration of 50 parts

per million seen in some, but not all, aluminum-rich Allende minerals (Lee et al., 1977 op. cit.) and the much smaller concentration (less than 1 part per million) that could be maintained there by supernova explosions. Thus the observed Allende concentrations of excess ^{26}Mg are still too large to be interpreted as being the average interstellar concentration. If the ^{26}Al was actually once alive in the Allende minerals seen today there must have been some source of ^{26}Al enhancement in the solar cloud as it was collapsing to form the solar system. This is the reinterpretation that Cameron now advances and which is consistent with a common meteoritic interpretation that the ^{26}Al was alive in the minerals at the time of their formation.

Whatever the source of the ^{26}Al observed today, those objects are necessarily ejecting 4 M_o per million years into the interstellar medium. By contrast supernova eject 24 M_o of new stable aluminum and stars reinject 60 M_o of old stable aluminum over the same million years. Arguing that all of these ejecta condense into refractory aluminum-rich solids as they leave their respective sources, that the ^{26}Al decays to ^{26}Mg within the resulting mixture of well mixed dust grains, Clayton reasoned that the ratio $^{26}Mg/Al = 0.04$ results within the aluminum-rich dust. This high interstellar correlation of excess ^{26}Mg with Al could not have been totally removed by evaporation, because the Allende minerals carry other isotopic anomalies that demonstrate that they were not evaporated totally at any stage prior to their assembly. Thus, the ^{26}Mg-Al correlation observed in Allende minerals may be a manifestation of a cosmic chemical memory (Clayton (1985) Geophys. Res Letters submitted).

At the present time, it is still uncertain whether the ^{26}Al was alive *in situ* or if it is primarily or partly a fossil. The data may well reflect both aspects. Paradoxically the gamma ray observations have raised the plausibility of both options! Searches for other extinct radioactivities, especially ^{41}Ca, ^{53}Mn and ^{60}Fe are badly needed and are in progress (R. Clayton, personal communication), because their presence or absence may point the way to the correct interpretation. This entire issue remains one of the most significant controversies about possible interrelations of circumstellar dust and meteoritic aggregates.

ii) Chemical Fractionations (Circumstellar)

It has been common to believe that thermal condensation sequences produce the same minerals that they would in thermal and chemical equilibrium, even during supernova expansions (e.g., Lattimer et al., 1978 op. cit.). If that assumption were true, it would imply that virtually all of the dust that has been ejected from the stars exists in refractory condensation sequences, so that the interstellar medium would be heavily fractionated with respect to these refractory elements. (Note: "fractionated" in this chemical context implies only that the elements are not microscopically mixed in their cosmic abundance ratios (e.g., Si/Fe=1), but instead reside in chemical structures (e.g., $MgSiO_3$) that have fractionated them microscopically. It is not taken to mean that averages over large volumes have variable abundances, although that too many occur for dynamical reasons.) If the elements are microscopically fractionated in the circumstellar origin of ISMD, the SSD will in part remember that fractionation, perhaps even in macroscopic meteoritic samples (Clayton and Ramadurai, 1977, Nature, 265, 427). However, simplistic models of circumstellar grain formation which rely on the attainment of "equilibrium" in the turbulent ejecta of stars undergoing mass loss have often been criticized by Donn (e.g. 1978, Protostars and Planets, 100-111). Specifically, Nuth and Donn (1981, Astrophys. J., 247, 925) have shown that thermal equilibrium is not attained in such regions due to cooling via molecular radiation while Donn and Nuth (1985, Astrophys. J., 288, 187) demonstrated that even nucleation theory can not be successfully applied to this process. Detailed grain models based on "equilibrium condensation" in stellar sources therefore seem rather implausible. The challenge in the present context of interrelationships between ISMD and meteoritic material is to find and describe realistic condensation and aggregation histories that map ISMD chemical fractionation onto meteoritic fractionation. This can be illustrated as a question: Does the tendency for meteoritic Mg to exist in oxides while Fe exists in metal and sulfides have any connection to the corresponding SUNOCON fractionation, or have those meteoritic fractionations been established in the solar system itself? That question is then generalized to others of a similar nature.

The reader must be reminded that one interrelation may, but need not, imply another. For example, there may exist a connection between CIRCUMSTELLAR/INTERSTELLAR fractionation patterns without the existence of the corresponding relation to SSD fractionation patterns - for example if the SSD patterns were all established in the solar system without memory of prior fractionation. Isotopic systematics argue against that particular scenario, but admitting its possibility may help clarify often fuzzy distinctions.

A.2 Interstellar/Meteoritic

Section A.1 demonstrated the clear evidence for the survival of circumstellar signatures in meteoritic dust. With that backdrop one can ask about the ISMD/meteoritic connection, which has been controversial and hard to pin down.

i) Some ISMD must survive the origin of the solar system

This raises the question of just how much ISMD, and which part of it, has survived and to what degree it has remained unaltered. The minimum requirement would seem to be that at least part has survived until at least a portion of it has been aggregated into larger accumulations so that its isotopic fingerprints remain on the final product even after some metamorphosis. A much stronger definition of survival, and therefore a less likely version, would be that interstellar dust particles themselves remain imbedded in meteorites. Between these extremes lies a spectrum of degrees of partial survival. This is a frontier research question. That the amount of unhomogenized material is large is attested to by macroscopic aggregates having 5% excess of ^{16}O and 10% excess of ^{50}Ti (Fahey et al, Lunar Planet. Sci., 16, 229 (1985)). However, suggestions that isotopic fractionation by distillation may have produced these anomalies still exist (Esat, Spear and Taylor, Lunar Planet. Sci., 16, 217 (1985)).

The principal observational evidence for the presence of some interstellar, as distinct from circumstellar, material in meteorites lies in the very high D/H values measured in several organic fractions of carbonaceous and

other primitive chondrites (e.g. Robert and Epstein, 1982). Enrichments in D of up to a factor of about 35 relative to the galactic value are observed. The only known mechanism capable of generating such an enrichment is the isotopic fractionation associated with ion-molecule reactions taking place at very low translational temperatures. Such reactions are inferred to be responsible for the even larger D enrichments observed astronomically in molecular clouds (e.g. Watson et al., 1977). Consequently, the idea has become widely accepted that at least part of the D found in primitive meteorites stems from molecules formed in such interstellar clouds (Geiss and Reeves, 1981, Astron. Astrophys, 93, 189; Kerridge, 1983, EPSL, 64, 186). Note, however, that to a certain extent this is an argument by default; a more rigorous observational connection between meteoritic organic matter and interstellar chemistry would be most desirable.

Recently a new set of fine-grained primitive extraterrestrial materials has become available through stratospheric dust collections of which the most challenging subset is formed by chondritic Interplanetary Dust Particles (IDP's) (Brownlee et al., 1977; Fraundorf et al., 1982; Mackinnon et al., 1982). The morphology of chondritic IDP's varies from non-porous to highly porous, fluffy particles commonly referred to as Chondritic Porous (CP) IDP's (Rietmeijer, 1985). The large D/H fractionation ratios of many chondritic IDP's (Zinner et al., 1983) suggest that this new class of extraterrestrial materials may be more primitive than the primitive (carbonaceous) chondrite meteorites.

Chondritic, including CP, IDP's are essentially cosmic sediments in the sense suggested by Wilkening (1978) and McSween (1979) for matrices of carbonaceous chondrites. The IDP's are heterogeneous, non-equilibrium mixtures of high- and low-temperature minerals (cf. Wood et al., this volume). Of the varied mineralogy of these IDP's, summarized in McKay et al. (1985), grains of Bismuth metal (Mackinnon and Rietmeijer, 1984), Titanium metal (Mackinnon and Rietmeijer, 1983) and single crystals of Tin or Tin dioxide (SnO_2) (Fraundorf, 1981; Rietmeijer and Mackinnon, 1984) and Titanium-oxides (Rietmeijer and Mackinnon, 1984) underline the very primitive nature of IDP's since these minerals appear to be absent in carbonaceous chondrites. These minerals sug-

gest that chondritic IDP's provide a window through which we may view individual remnant ISMD grains which, even in the carbonaceous chondrites, may already have lost their identity through metamorphosis (Rietmeijer, 1985).

ii) A specific and correct theory for the aggregation of ISMD (where and when) and for the environment (especially thermal) of those aggregates is needed to evaluate survival scenarios. Therefore, a continuing strong research emphasis must be on the physics and chemistry of aggregation.

Some aggregation may occur in the turbulent ISM itself. These aggregates will form cold. Aggregation could occur in the "mother" molecular cloud or in prior history. It is exactly at this point that one desires a complete description of the chemical constitution of the dust in the molecular cloud. Every detail of the chemical history will have to be followed in some statistical sense, and occasionally in an explicit sense. This formidable problem no doubt requires ISM dust science and meteoritic science to proceed iteratively.

Some aggregation may occur in the collapse of a turbulent cloud to a protosolar disk (Cameron, 1975 Icarus, 24, 128). Chondrule sized (0.1 mm) bodies may be aggregated in profusion at this time accompanied by a significant rise in the temperature of grain aggregates. Aggregation in the solar accretion disk itself might occur subsequently. Model calculations exist (Volk et al., 1978 Moon and Planets, 19, 221; Morfill and Volk, 1984 Astrophys. J., 287, 371). Chondule-sized objects are indicated.

Conventional wisdom among meteoriticists is that the components of chondrites (chondrules, CAIs, matrix dust) were formed in a wide variety of places and temperature regimes, after which they mixed into cm-size aggregations which had enough mass to sink to the nebular midplane. There the dust-rich layer became gravitationally unstable, and aggregation into planetsimals began. Wood (1985a, b) however, has argued from the absence of preserved cm-size structures in chondrites that this particular stage of coalescence did not occur. He also argues from the fact that various chondrite subtypes contain distinctive types of chondrules (etc.) which did not mix with one another

prior to accretion, that in fact chondrite aggregation must have occurred very promptly after the high-temperature events or processes that created the chondrules, probably within a few orbital periods. A manifestation of gravitational instability seems required that does not require concentration of the chondritic solids at the nebular midplane.

Certain observations allow constraints to be placed on the manner in which processed grains aggregated into meteorites in the intermediate parts of the solar nebula. The first of those observations is that each different type of chondritic meteorite consists of components (CAIs, chondrules, matrix) that are usually different from those in other types e.g. (CAIs that are coarse-grained and centimeter-sized are found only in CV chondrites such as Allende, while ferromagnesian chondrules (though almost universally present) differ in composition and size range in the CV, CO, CM, CI, enstatite and ordinary chondrites. There was therefore, very little cross-mixing of components between the different chondrite formation regions. The only escape from this conclusion would be if the ingredients are altered by the cross-mixing; that is, if the ambient temperature and chemistry alter each ingredient as it migrates from region to region. On the other hand, some common chondrule types are apparently indistinguishable whether they occur in CM, CV, ordinary or enstatite chondrites (Scott and Taylor JGR, 88, B275 (1983)).

A second observation is that the main belt asteroids (the probable source of meteorites) are stratified into a series of concentric zones which change systematically in composition outwards from Type E at 2 AU to Type S to Type C to Type D at 5 AU (Gradie and Tedesco, 1982).

A third observation is that all of the various chondrite types, though made up of quite different components, nevertheless contain approximately solar relative proportions of non-volatile elements. This suggests that the various chondrite types formed as separate, almost closed, systems and is consistent with the absence of cross-mixing noted above.

A fourth and very important observation is that all chondrites have some components (CAIs, chondrules) that were made at high temperature (>1000°C) and

then cooled within minutes to days (Paque and Stolper, 1983; Hewins, 1983). This requires the high temperature regions to be of quite limited volume and/or duration. It also suggests that solar radiation was not the heat source. Taken together with the earlier observations, it further indicates that refractory components were not made near the sun and transported outwards by turbulence.

The fifth and final observation is that the various components are randomly mixed within each meteorite. This means that formed components were placed into "parking" orbits where they mixed with other components but did not clump together to produce the meteorite parent body until after all its components had been formed.

Aggregation of parent bodies from planetesimals occurs subsequently. A huge literature exists (e.g. Hayashi _et al._, 1984 in _Protostars and Planets II_). This more-or-less standard theory relies on larger bodies gathering smaller ones by collisions during the collisional evolution of the disk; but alternate ideas exist.

A detailed "hydromagnetic-planetesimal" model for the agglomeration of larger bodies from smaller bodies around a magnetized spinning body (either the sun or a planet) has been developed by Alfven (1954) and subsequently extended by Alfven and Arrhenius (1975). In this model the hydromagnetic transfer of angular momentum from the magnetized, spinning central body to the surrounding, infalling, dusty plasma results in the formation of a circum-solar or circum-planetary disc in the equatorial plane. There are several mechanisms proposed for the spontaneous radial break-up of this disc into concentric tori. If the collisions between dust grains within each of these tori were sufficiently "sticky", they would lead to the gradual formation of larger bodies in the equatorial plane. A similar idea of inelastic collisions between bodies in nearly identical orbits leading to larger bodies, has also be discussed by Safronov (1967).

iii) _The thermal history of aggregates_ must be known to evaluate the loss of volatiles and all subsequent metamorphism. A specially interesting

problem is the origin of chondrules. What are the sources of heating that must be evaluated? Many have been suggested, but the following look most relevant, in chronological sequence of their possible occurrence.

(a) Cold interstellar aggregates may be heated by aerodynamic drag after passing through the standing gas shock associated with the supersonic infall of matter toward a solar disk (Wood, 1984 EPSL, 70, 11). Wood assumes an infall speed of 10 km/sec dissipated as dust falls onto the nebular disk. The subsequent chemistry and aggregation deserves much study. Interstellar grains and grain aggregates would not be stopped at the shock front of course, but would continue through the decelerated gas at (initially) the prenebular infall velocity; e.g. on the order of 10 km/sec. Aerodynamic drag would decelerate and heat the grains. Wood (1984) has identified conditions under which drag heating could turn interstellar dust into chondrules and CAIs. The effect appears to be important only where dust-enriched parcels of interstellar gas impact the solar nebula: in the absence of an optically thick environment near the nebula surface (such as a high concentration of dust would provide) drag-decelerated objects would cool too efficiently by radiation to be heated significantly. A corollary of this situation is that some interstellar grains (e.g. - those which did not enter the nebula in dust-rich ensembles) would not be heated, and might still retain their interstellar properties when incorporated in chondritic planetesimals.

(b) Exothermic chemical heating occurs whenever highly disequilibrated aggregates are heated sufficiently to trigger the exothermic rearrangement. Clayton (1980, Astrophys. J. (Letters), 239, L37) has suggested this as a heating source capable of both chondrule formation and thermal metamorphism of small planetesimals. Aggregation of chondrule-sized clumps would have to occur in such a way that the clump remained cold enough that its chemical rearrangement not be triggered. Such dust aggregates might subsequently be heated by ambient temperatures in the accretion disk, at which point chemical runaway could occur.

(c) The ambient gas temperature within the solar accretion disk could be high enough to thermally anneal amorphous grains or even vaporize presolar

materials. The source of this heat is the "frictional" dissipation associated with viscosity and the outward transport of angular momentum (e.g. Lin 1981 op. cit.; Morfill and Volk (1984) op. cit.). The highest temperatures (>1000K) lie closest to the sun with colder temperatures (<500K) in the likely regions of meteoritic accumulation. Dust aggregates may be turbulently transported between these regions by a radial random walk (Morfill and Volk, 1984 op. cit.). This situation raises the possibility of adding to parent bodies dust aggregates having a wide spectrum of thermal histories. In this model the aggregation history and the thermal history are coupled problems. But if it is to be effective, this radial mixing from regions of different temperature must circumvent the chemical arguments against mixing detailed above by allowing the aggregates to alter during transport.

(d) Lightning strokes may heat selected portions of the disk.

(e) Ohmic dissipation resulting from motion through magnetic fields could heat larger bodies over hundreds of thousands of years.

(f) Parent-body heating and alteration may occur after its accumulation either by trapped heat, by radioactive energy release, or by chemical energy release. These stages of thermal metamorphism are a significant part of meteoritical science (c.f. Meteorites, R. T. Dodd, Cambridge University Press 1981, Chapter 6, or the meteorite section of this report). Some meteorites (chondrites) are magmatically differentiated by this process, and some have been altered by "geothermal" fluids.

iv) Nonthermal effects on presolar grains must be evaluated for tracers that can reveal something of the time spent in the ISM.

a) Sputtering of small refractory grains may be expected to produce an isotopic fractionation between the fraction of the element remaining in the grains and the fraction in the interstellar gas. Clayton (1981, Astrophys. J., 251, 374) has advanced this as the mechanism for producing the large isotopic fractionation found in certain anomalous Allende inclusions. A more detailed scenario for this fractionation is needed. The basic idea is that as

sputtering grinds grains down to their most refractory centers it also establishes a skin depth that is isotopically fractionated. On general grounds one expects light isotopes to be removed somewhat preferentially by the sputtering. If the element is very refractory, so that it resides overwhelmingly in grains, the pool of gas phase isotopes may be considerably lighter than the condensed portion. Mechanical separation of dust from gas, or of sputtered skins from interiors, can result in bulk isotopic fractionation. One way of mapping this onto a chemical memory is to recondense the gas onto small grains, employing grain-size effects to produce bulk macroscopic isotopic fractionations (Clayton, 1980 EPSL, 47, 199).

The sputtering of sequentially condensed refractory elements may also play a key role in maintaining a higher gas concentration of less refractory elements. The most refractory elements remain most shielded from sputtering. For example, the fraction of Al in ISM gas may be much less than the fraction of Mg because the Al is not nearly as exposed to sputtering as Mg is. Although the related phenomena are difficult to observe in the astronomical setting, they may define important relationships between ISMD and meteoritic dust.

b) Cosmic rays cause spallation reactions within grains. These may produce isotopic anomalies (Ray and Volk, 1983 Icarus, 54, 406). Heavy cosmic ray nuclei also leave ion tracks that may be exposed by etching. A large literature exists for study of these effects during solar system history, but the presolar component is harder to identify.

c) Higher speed grain-grain collisions ($v > 1$ km/sec) are normally thought to be disruptive to grains. But is it possible, if ISMD has a composite structure containing both refractory components and mantles, that clumps of larger refractory-rich aggregates can be grown in violently turbulent settings. Clayton (1977 EPSL, 35, 398; 1981 Astrophys. J., 251, 374) has argued that this scenario could conceivably prepare parents of the CAI's. Elmegreen (1982 Astrophys. J., 251, 820) has argued that this could come about in the wake of ISM supernova shock waves, where ample sputtering will also be expected.

The major dust processing agents in the interstellar medium are interstellar shocks. The average dust grain has passed through one to ten 100 $km\text{-}s^{-1}$ interstellar shock waves. In each of these shock waves, a grain composed of N atoms is struck by 10 N protons, N He^+ and He^{++} ions, and perhaps 10^{-2} N carbon, oxygen and nitrogen ions, with kinetic energies of order 100 m eV (where m is the mass in atomic units of the ion). These ions both sputter the surface of the grain and are implanted in the grains. The former process may cause some small degree of isotopic or chemical fractionation as lighter atoms or more weakly bound atoms preferentially sputter. The latter process may make the grains (or their surfaces) resemble lunar surfaces which have been exposed to the solar wind. In addition, in each shock wave a typical grain is struck by smaller grains with relative velocities of 5-100 $km\text{-}s^{-1}$. The more energetic collisions could certainly result in vaporization and shattering. The less energetic collisions may lead to cratering of the larger particle. The vapor may later be redeposited on colder interstellar grains, causing a distinct mantle or surface layer to appear on the grain. **Thus, an interstellar grain may be recognizable because it has been sputtered, ion implanted, cratered, and mantled.**

Grain-grain collisions play an important role everywhere there are grains present. Low velocity impacts ($v \ll 1 km/s$) generally lead to accretion of both particles. This effect plays a major role in the early nebular disk, and at the present time in dense planetary rings. The relative speeds in the latter case are in the range of cm/s. However, recent laboratory experiments with impacts of projectiles into low density materials (i.e. $\ll 1 g/cm^3$, like styrofoam) by Werle, Fechtig and Schneider (1981, Proc. Lunar Planet. Sci., 12B, 1641) show that a major fraction of the impacting body can be recovered almost intact even at speeds as high as 6 km/s. This speed is not an upper limit but is simply the maximum speed at which the experiments were performed. This situation may be important for the capture of interstellar particles in low density snow on the surface of comets in the outer solar system, where relative speeds are at a minimum.

High speed collisions ($v \gg 1 km/s$) generally lead to the destruction at least of the smaller of the two colliding particles. The effects are based on

laboratory experiments which were described by Gault and Wedekind (1969, JGR, 74, 6780), Gault (1973, The Moon, 6, 32) and Fujiwara et al. (1977, Icarus, 37, 277). These experiments were performed with mm-sized projectiles at speeds below 10 km/s onto glass, rock and metal targets. Experiments at higher speeds (>20 km/s) with micron-sized particles are described by Hörz et al. (1975, Planet. Space Sci., 23, 151). The latter experiments primarily studied cratering and therefore, pertain to erosion of the larger body.

High speed collisions between two particles lead to the destruction (evaporation) of the smaller of the two particles while the larger one may be just cratered or fragmented. In the first case the excavated material will be solid particles, to a smaller extent liquid droplets and only the order of the small particle mass will be evaporated. The total mass excavated (i.e. the crater volume) depends on the kinetic energy of the smaller particle in the reference frame of the larger particle and of course, on the materials involved.

In interplanetary space, however, even more important is the case where the kinetic energy of the collision is sufficient to fragment the larger particle completely. A discussion of the relative importance of both cases can be found in Dohnanyi (1972, Icarus, 17, 1). Catastrophic collision is more important than the slow erosion by cratering because much more mass (of the large particle) is shattered than is excavated in the cratering process. For example, at an impact speed of 10 km/s, a particle of mass m_1 can fragment a particle of mass $m_2=4\times10^5 m_1$. On the other hand, a slightly smaller projectile $m_3=0.5m_1$ will only excavate a crater in a particle of mass m_2. This ratio of the mass of the target particle m_2 to the mass of the smallest projectile m_1 which will still catastrophically destroy the larger particle depends on the square of the relative speed v.

The effects of catastrophic collisions are also important for a population of particles. If particles are all of the same size, then a collision will destroy and perhaps even vaporize both. But if there is a size distribution, e.g., $g(m)=m^{-x}$, then the most probable catastrophic collision of a given particle is with a much smaller particle because they are more numerous. The

fragments may follow a size distribution of the type $h(m)=m^{-y}$, where y=0.83 (Fujiwara et al., 1977). Therefore, fragmentation could change the original size distribution. Dohnanyi (1970, JGR, 75, 3468) has shown that only a distribution with a population index (x) of 11/6 is stable against fragmentation and will not change with time. This is the case for the distribution of asteroids. If the population index is larger than 11/6, then more particles are destroyed in a given mass interval than are generated by collisions of larger particles in the same mass interval. This is the case for large ($10^{-5}g<m<10^{2}g$) interplanetary grains (x=1.34) which need to be replenished by a source (e.g. from comets). If the population index is smaller than 11/6 then more particles are generated by collisions then are removed from the same mass interval. An example for this case are zodiacal particles ($10^{-10}g<m<10^{-5}g$) which are produced mainly by fragmentation of meteor sized objects ($m>10^{-5}g$), faster than they are destroyed by mutual collisions.

v. Search for Primitive Polycyclic Aromatic Hydrocarbons

Polycyclic Aromatic Hydrocarbon (PAH) molecules have recently been suggested as the source of IR emission bands (Leger and Puget, 1984, Astron. Astrophys., 137, L5). This identification seems to be a reasonable hypothesis but only indicates the presence of a molecular family because many members of this class of molecules can have the same IR vibrations (C-H, C-C modes). Laboratory determination of the visible spectra of PAH is being undertaken, but a great difficulty is the criterion for selection of the molecules to study (there are $>10^{4}$ molecules for a carbon atom number between 50 and 100). PAH molecules have been detected in meteorites (e.g. Hayatsu and Anders, 1981). If one could find such molecules in situations where there is some hope that they are primitive (in the sense of having the original chemical formula) it may be a most interesting guide to the selection of species for laboratory studies and potential spectroscopic identification.

vi. Interstellar Organic (Biogenic ?) Material

In a series of papers over the past decade, Hoyle and Wickramasinghe have argued that organic matter is the major source of interstellar opacity

(Hoyle, F. and Wickramasinghe, N. C., 1977, Nature, 268, 610). Their efforts have embraced everything from detailed fits of the wavelength dependence of interstellar extinction to theoretical arguments about the need to utilize organic compounds. If they are correct, these compounds will be the natural abundant precursors of the carbonaceous matter found in meteorites.

But there is an even more important connection between these interstellar particles and the solar system record -- life itself. Highly controversial and not accepted by most of the scientific world, they have argued that the chemical memory structures that characterize life did not originate on Earth, but were instead inherited by Earth from a larger cosmic evolution (Hoyle, F. and Wickramasinghe, N. C., 1979, Astrophys. Spa. Sci., 66, 77). They have stressed that many very deep issues are involved, even our concepts of intelligence and of the correct cosmological theory. We must at least admit that if they are correct, it is the most important connection of them all to a cosmic memory. Because of its radical nature, much of their writing has gone straight to the public (e.g. Evolution from Space, J. M. Dent and Sons, London 1981).

B. Planetary Record

Postulated relationships between the structures of planets and the structure of ISMD are much harder to pin down because the planets have been so chemically active. The question may perhaps be asked this way: "What properties of planets owe their existence to the actual structure of ISMD; i.e. What would have been different if the dust structures had been different?" Little consensus exists on these clues because they depend upon a theoretical picture of dust aggregation and modification leading to the growth of planets. Because the initial generations of dust structures are now gone, one is concerned with fine effects in the bulk composition of planets, and these fine effects are attributable to initial properties of the dust (ISMD) only with grave uncertainty at present. Studies of the transport and aggregation of dust in a model of the solar disk (e.g., Lin, 1981, Morfill and Volk, 1984, op. cit.) seem at present to offer the most likely chance of establishing a connection. But even so, an almost exactly correct description will be needed

to evaluate the small fractionation effects on the bulk compositions of planets. Planetary atmospheres could, in principle, record volatile-rich accretion over geologic time.

C. Cometary Record

Unlike meteorites, the birthdates of comets are unknown, although on good grounds they are also believed by most astronomers to have formed early in solar system history. If that is the case, comets should carry some memory of the ISM dust from which they probably formed. Although connections to ISMD then exist, the hard task in this case is the measurement of the properties of cometary material. An extensive literature exists and can be approached through Comets (University of Arizona Press: Tucson 1984). Some *in situ* measurements may already exist if cometary breakup is a major souce of interplanetary dust particles (IDP's - see Walker's review). A returned cometary sample could become the single most informative piece of evidence of this relationship, but the proposed flybys may be almost as revealing.

Whether the comets in the Oort cloud ($d > 3x10^4$ AU) were formed in-situ or were formed in the trans-Neptunian region and kicked out by the gravitational perturbations of these outer planets is still an open question. Whatever their origin, however, it is generally regarded that comets, by virtue of their small masses (leading to almost no internal heating or weathering and a negligible number of high-velocity meteoritic impacts) perhaps represent the most pristine material in the solar system. Consequently, a proper understanding of their chemical composition and physical structure (e.g. do they show a hierarchical granular structure similar to Brownlee particles) could give us important clues both to the physico-chemical environment in which they formed, as well as the basic physical processes that led to their formation. For this reason, a sample return mission to a comet in the future, following the present fly-by missions to comets Halley and Giacobini-Zinner and the proposed rendezvous mission, possibly to comet Wildt2, should be strongly supported.

1. The relationship of cometary volatiles to the ISM. The relationship of cometary volatiles to interstellar dust is unclear because it is not known whether the volatiles condensed as mantles on grains in dark clouds long before accretion into comets or condensed in the pre-solar nebula. A few points bear on the condensation process and subsequent history.

a. If S_2 is truly resident in the cometary nucleus and is not a rapidly produced daughter product, it constrains the history of the grains. In particular, it requires irradiation of sulfur compounds in grain mantles and it requires that the irradiated mantles remain very cold ($T < 30$ K) from the time of irradiation until accretion into the nucleus (A'Hearn et al. 1983, Ap. J. (Lett.), 274, L99).

b. The D/H ratio in H_2O (only upper limits exist now but better numbers will exist within 1 1/2 years) constrain the condensation process of H_2O. Condensation of H_2O on grain surfaces should lead to a temperature dependent fractionation. Since the ice band is readily observed in dark clouds, it is likely that the condensation process should take place there. Better theoretical models of the fractionation, allowing for time dependence, will be needed.

2. Cometary Refractory Grains. The large (compared to diffuse ISM) grains which are presumably friable and porous, require a very gentle aggregation process, either in clouds or in the pre-solar nebula. Do the clouds completely shield the grains from the destructive shocks of the diffuse ISM?

3. Need for In Situ Measurements. In situ experiments (e.g. from the CRAF mission) could test whether or not the C depleted from volatiles has gone into refractories by measuring the vaporization mass spectra of dust. Such a mission can, in principle, look for the isotopic anomalies found in meteorites, although getting sufficient sensitivity in flight instruments may be difficult.

II. INTERRELATIONSHIPS TODAY

A. "IDP" Captured from ISM

Because the spectrum of origins of IDP's is not known, the possibility exists that some may be captured from the ISM. Entry of ISMD into the solar system happens at all times, but especially during those epochs when the solar system passes through ISM clouds. The probability frequency of the latter is discussed in several papers in the book The Galaxy and the Solar System (University of Arizona Press: Tucson 1985). Capture in recent times would present us with particles related to ISMD today. It is still not known how large ISMD particles can be, or even if macroscopic ISMD particles exist.

1. Estimates of total accretion of interstellar grains onto Earth's Surface. Over the earth's total history, probably about a dozen clouds of density n_H=1000 cm^{-3} have been encountered. Clouds of such density will suppress the heliopause to within 1 AU of the Sun, so that the dust particles in these clouds should accrete onto the earth's atmosphere unimpeded by destruction processes associated with the solar wind. It is simplest to assume that the radiation pressure on the grain balances the Poynting-Robertson effect, a reasonable assumption for a typical a 0.1 micron particle expected for n_H=1000 cm^{-3} clouds. But see the discussion of the size distribution below.

A density enhancement of a factor of 3-10 over the ambient interstellar density is expected at 1AU for an average relative sun-cloud velocity of 20 km/s. If the earth has encountered a dozen such clouds over its history, and if each cloud encounter lasted about 10^6 years (i.e. a cloud length of 10pc), then a total integrated flux of about 0.06 g cm^{-2} is expected on the earth's surface, or a total accumulation of $9x10^{20}$ grams. At an average grain density of $3g/cm^3$, this is enough to build about 25 mountains the size of Mount Everest. This interstellar component is unfortunately swamped by the much larger influx of solar system micrometeorites (Barker and Anders, 1968, Geochim. Cosmochim. Acta, 32, 175).

2. Interstellar "IDP" Effects on Lunar Soils. At the present time the solar system is apparently located in a region of space that is not densely populated with interstellar gas and dust. However, this has almost certainly not been true for its entire history. At various times in the past, the solar system must have encountered dense, interstellar gas/dust clouds (see The Galaxy and the Solar System (Tucson 1985)). In principle, the record of such encounters could be preserved in individual crystals of the lunar regolith. Individual lunar soil grains have typically been exposed for 10^4 years at the very surface of the moon. Crystals removed from different depths and from different cores were exposed at various times in the past - in some cases at least 10^9 years ago. The record of surface exposure is manifested by the presence of micrometeoritic impact craters, solar wind implanted ions, and solar flare tracks. Passage through a dense dust cloud would produce crystals with a higher average density of impact pits relative to implanted solar wind ions than crystals exposed at the lower surface. Initial attempts to look for an effect were defeated by the presence of glass splashes on grain surfaces which masked the Mg contribution which was being used as a tracer of implanted solar wind. Recent advances in instrumentation have made it possible to re-examine this question using nitrogen as the solar wind tracer. Since the indigenous nitrogen concentration is low on the moon, its use as a tracer of solar wind exposure should not be compromised by the presence of glass splashes. While admittedly an extremely difficult experimental problem, it is still worthwhile to attempt to use lunar samples to establish a fuller record of the history of the solar system than has thus far been done. Again, however, it is necessary to separate the interstellar component from a much greater influx of more mundane solar system particles (see Anders et al., 1973, The Moon, 8, 3).

3. Dynamical Aspects of Today's Intersellar/Interplanetary Connection. Interplanetary matter contributes to the interstellar medium via the injection of small particles ($m<10^{-12}g$) into hyperbolic trajectories under the influence of radiation pressure. There are two processes which generate these small particles: (1) evaporation of comets in the inner solar system with the subsequent release of cometary dust, and (2) collisional fragmentation of larger interplanetary meteoroids. The outflux of both types of particles from the

solar system is of the order of 10 tons per second (Delsemme 1976, Lecture Notes in Physics, 48, 314; and Grün et al, 1985, Icarus in press).

On the other hand, interstellar grains will enter the solar system and may be observable there. There are certain dynamical processes which affect the trajectories and which lead to a dispersion of incoming interstellar grains. Radiation pressure reduces the gravitational attraction by the sun. The parameter which quantifies this effect is the ratio of the radiation pressure force F_{rad} over the solar gravitational force F_{grav}: beta=F_{rad}/F_{grav}. This ratio is a function only of particle parameters such as the size (s), density (p) and optical scattering efficiency Q: beta=Q/sp. For micron- and submicron-sized particles beta reaches unity and may even exceed it. For smaller particles, it decreases (pure dielectric materials) or stays close to unity (absorbing materials). The effect of beta >1 for small particles is that they are repelled from the sun rather than being attracted by it. The result will be that these small particles reach only a minimum distance from the sun which depends on their incoming velocity.

Another effect is due to the interaction of interstellar grains with the solar wind. Solar wind ions impinging on dust particles also exert a repelling force on the grains which, for submicron-sized dielectric particles, may become the dominating force. Therefore, very small (<0.1 micron) dielectric particles are shielded from the inner solar system.

A third effect which acts to prevent small interstellar grains from reaching the inner solar system is the electromagnetic interaction between charged dust particles and the interplanetary magnetic field. Dust particles within the heliosphere will be charged positively because of the prevailing photoelectric effect, which exceeds the charging by solar wind electrons. The surface potential is estimated to be of the order of 10V independent of the solar distance (Rhee, 1969). The charged interstellar dust grains interact with the interplanetary magnetic field. For micron sized particles this force is only a small perturbation compared to the force exerted by gravity and radiation pressure. For 0.1 micron sized particles however, the electromagnetic force is comparable to the others. Morfill and Grün (1979, Planet.

Space Sci.) have shown that interstellar grains may be focused towards or dispersed away from the current sheet located close to the ecliptic plane, depending on the configuration of the overall solar magnetic field which varies with the solar cycle. Small charged particles entering the solar system at high solar latitudes will encounter only a unipolar field which will effectively repel them all the time.

The upshot of these considerations is that submicron-sized (<0.1 micron) particles made from either absorbing (carbon or metal rich) or dielectric (silicates) material will not reach the inner solar system. Their closest approach depends on their speed with respect to the Sun and on their exact compositon (pure dielectrics may get somewhat closer). However, particles larger than a micron are not repelled by the effects discussed above and may even be gravitationally concentrated in the solar system just as the interstellar wind is (Fahr (1974) Space Sci. Rev., 15, 483). Therefore, a crucial prerequisite for the capture of interstellar grains near 1AU is the existence of sufficiently large particles in the ISM. From in-situ interplanetary dust measurements (see interplanetary grain report) there are indications that some of the recorded particles may have an interstellar origin.

4. Alteration of SSD on Parent Bodies. Fortunately many minerals in chondritic IDP's may retain identifiable memory regarding previous events such as processes that affected the IDP's after accumulation and residence in a protoplanetary parent body (Rietmeijer, 1985-a; -b; see also Sandford and Walker, 1985 Ap. J., 291, 838), during their solar system sojourn and atmospheric entry. Prominent among these minerals are Epsilon (E-) carbide, poorly graphitized carbon, layer silicates and Bi_2O_3. The E-carbide (Christoffersen and Buseck, 1983) is of interest because it may be a residue of Fischer-Tropsch reactions which have been proposed by Anders and coworkers as a possible source of solar-system hydrocarbons (cf. Studier et al., 1972).

Rietmeijer and Mackinnon (1985-a) suggested that catalytically activated hydrous pyrolysis below about $300^{\circ}C$ may affect "hydrocarbon compounds" in chondritic IDP's to produce amorphous carbon. Continued heat-treatment at temperatures below about $500^{\circ}C$ induces graphitization resulting in the forma-

tion of poorly graphitized carbon (PGC) similar to PGC in carbonaceous chondrites (Rietmeijer and Mackinnon, 1985-b). The degree of graphitization is a potential cosmothermometer for primitive extraterrestrial materials (Rietmeijer and Mackinnon, 1985-b).

The debate on the origin of layer silicates in primitive extraterrestrial materials (carbonaceous chondrites) centers on the question of whether they are the result of low-temperature aqueous alteration (McSween et al., 1979; Bunch and Chang, 1980) or whether they have formed by direct vapor phase condensation (Lewis, 1972; Saxena and Eriksson, 1983). In general, layer silicates are common alteration products of anhydrous silicates. Recently it has been suggested that the alteration processes may take place at room temperature (25°C) or even below the melting point of water ice (Gooding, 1984; Rietmeijer and Mackinnon, 1984-a; Rietmeijer, 1985-a, -b).

Layer silicates have been observed in five IDP's -- IDP XP-36 (Brownlee, 1978); LOW-CA, a hydrated IDP; Skywalker and Calrissian (Tomeoka and Buseck, 1984; 1985-a; -b) and in CPA W7029*A (Mackinnon and Rietmeijer, 1983; Rietmeijer and Mackinnon, 1984-b, 1985-c). The most abundant layer silicate in IDP's is a smectite, or a mica of similar composition. A phase which may be comparable with the IDP layer silicate has been described from a fine-grained CAI in the Allende (CV) meteorite (Tomeoka and Buseck, 1982). Other, less abundant, groups of layer silicates in IDP's are chamosite or serpentine (Brownlee, 1978), a poorly crystalline Fe-rich layer silicate (Tomeoka and Buseck, 1985-a, -b; Rietmeijer and Mackinnon, 1984-b, 1985-c), Mg-poor talc and kaolinite (an Al-rich layer silicate) (Mackinnon and Rietmeijer, 1983; Rietmeijer and Mackinnon, 1985-c). Layer silicates in these IDP's are not similar to the predominant layer silicates in CM chondrite matrices and are also probably dissimilar to layer silicates in CI chondrites, although detailed Analytical Electron Microscope analyses on CI meteorites are not available (Rietmeijer and Mackinnon 1985).

Although the diversity of layer silicates in IDP's probably points to low-temperature alteration of IDP's in a proto-planetary parent body, the large stability fields of the IDP layer silicates render them generally un-

suitable to more precisely constrain the alteration process. One noticeable exception is kaolinite, the presence of which in IDP's suggests that (1) during solar system transit heating of the IDP was minimal and (2) low water vapor pressures may have prevailed in the IDP (Rietmeijer and Mackinnon, 1985).

In Chondritic Porous Aggregate (CPA) W7029*A single crystals of Bi_2O_3 formed via oxidation of Bi-metal in response to flash-heating of this aggregate during its atmospheric entry. The simple cubic structure of this oxide indicates that this mineral formed below about 300°C (Mackinnon and Rietmeijer, 1984). This low entry temperature agrees well with the preservation of nuclear tracks in olivines found in IDP's [Bradley et al., 1984].

In general, a careful study of the mineralogy of IDP's may reveal detailed pieces of its memory, which may eventually enable us to isolate unaltered ISM dust grains in chondritic IDP's and even in primitive meteorites.

5. Searching for relatively Unaltered Material. The look we get at the properties of presolar material through the study of meteoritic material is clouded and obscured by the event of solar system formation which obliterated much of the information we seek. Although continued study of the meteoritic record will increase our knowledge of presolar material, it is imperative to concentrate on material which is primordial, i.e. which has not been effected by the solar system formation event. This includes:

a) Intensified work on interplanetary dust particles collected in the stratosphere (IDPs). Judged by the percentage of IDPs exhibiting D-excesses, these particles as a class of material are more primitive than primitive meteorites.

b) Collection of interplanetary dust particles from known sources. Orbital parameter determination in conjunction with collection of material in space would enable us to distinguish between grains of cometary and asteroidal origin as well as (hopefully) present day interstellar grains. Experiments of this type have been proposed for implementation on the Space Station.

c) Collection of cometary material during a fly-by mission.

d) Collection of material during a comet sample return mission (solid material and gas).

e) Possible future missions dedicated to the collection of dust and ice from the rings of the outer planets.

All experiments designed to trap and analyze the atoms from impacting interplanetary dust particles are currently orbiting the earth on the Long Duration Exposure Facility (LDEF I). The spacecraft is due to be returned to earth at the end of the Summer 1986. Both elemental and isotopic measurements (with a precision of 1/1000) will be made. One interesting question to be answered is the extent to which particles collected in this way will show similar isotopic effects to those that have already been measured in IDPs collected in the upper atmosphere (Walker, this workshop). A sneak-preview of the LDEF I experiments is provided by the return of parts from the Solar Maximum Satellite which show impacts from chondritic and iron-sulfide micrometeoroids (Schramm et al., 1985, <u>LPSC XVI</u>, 736).

The current experiments are only crude precursors to what could be flown to identify, collect, and analyze cosmic dust from known sources. With a reasonable extrapolation of existing technology, it appears feasible to measure the time of arrival of individual particles and, more important, to determine their velocities i.e.: <u>the orbital parameters of particles whose isotopic composition could be measured</u>. An array of many individual "active" capture cells - those that would measure the location, velocity, and time-of-arrival has been proposed as a potential space station experiment (see Bank's report on the scientific uses of the space station; also Zinner and Walker, this conference). Individual cells containing impacts with "interesting" orbital parameters could be removed periodically from the large array and returned to earth for detailed study.

Interesting orbits would be those which indicated that the particles originated either from specific comets or came directly from the interstellar

medium, that is, those particles whose orbits were out of the plane of the ecliptic and/or whose velocities were equal to or greater than the escape velocity of the solar system.

Although it is only conjectural at this point, comets appear to be a promising place to look for primordial solar system matter (NAS report on small bodies) and interstellar dust that escaped drastic modification during the formation of the solar system.

With existing laboratory instrumentation, it is possible to obtain precise isotopic measurements on impacts from 10 micron particles. The flux of interstellar particles of this size traversing the solar system cannot be calculated exactly from current knowledge, but it is certainly low. If such particles could be captured and studied it would open up a new chapter in experimental astrophysics. However, even if only interplanetary particles were measured, the experiment, which has been given the acronym ODACE (Orbital Determination and Capture Experiment), (Walker and Zinner, this conference), would contribute important new knowledge about primitive materials.

B. IDPs Stored in Regoliths

If solid bodies have accreted ISM dust during solar system history, IDPs liberated during collisions with those bodies may be directly related to ISMD. This rather remote connection of current IDPs to the ISM will be very hard to establish even if it exists.

C. Circumstellar Material Around Other Stars

An entirely new perspective on the relationship between interplanetary and interstellar material may arise from studies of the solid material orbiting other stars, first recognized in IRAS data and recently confirmed with optical observations. This field of investigation is sufficiently new and difficult observationally that the level of detailed characterization of the material which will eventually be attained is difficult to project. However, these new samples of material which have survived the transition from the

interstellar medium to long-lived near-stellar disks, should, by virtue both of their similarities to and differences from solar system material, provide new clues to the character of the primordial material and the changes inherent in this material resulting from stellar formation.

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PARTICIPANT COMMENT SESSION - DAY 3

NASA DUST GRAIN WORKSHOP

The scientific organizing committee and working group chairmen met during a reception after dinner on the second day of the conference to discuss the agenda for the following morning. During this meeting it was suggested that it might be interesting if everyone present were given the opportunity to "ask one burning question" or "speak his or her mind" on a single issue which was related to the conference, but not necessarily within their own particular area of expertise.

Because many people objected to simply "making a list of questions," it was decided that if someone could answer a question in one or two lines, this would be done. If the question was the spark to considerable controversy; however, discussion was halted on that topic and continued at leisure after all questions had been asked. The edited transcript of this experiment is contained in the following pages and makes rather interesting reading. A number of the questions would make very respectable thesis research topics, while others clearly define areas where interdisciplinary approaches are required.

As a point of information, if a speakers' name appears in all capital letters, the statement which follows was his initial question or comment. Subsequent comments on this topic were made by those individuals in which only the first letter of the name is capitalized.

A'HEARN: As people presumably realize, you can look at the grains in comets that have been reported to produce all of the interplanetary particles and we can measure very few properties, e.g., things like the spectral reflectivity and the albedo. Would somebody please tell me what the corresponding properties of the collected particles are. What color are they?

Zinner: They are black mostly.

A'Hearn: I realize they're dark, I want to know how dark? And by black, do you mean the reflectivity is neutral across the optical?

WARK: In the region around a protostar where grains are falling into an increasingly warm and hot environment, I'd be interested to know what processes happen, particularly to sulphide grains, e.g., whether those grains melt or volatalize, and whether there is any coagulation of molten grains or indeed of ferromagnetic grains and under what conditions could one have clumping of grains in the infall from the interstellar medium.

ALLAMANDOLA: It's more of a question that I think we all are faced with. We constantly hear about the need for lab data and this is something Bob mentioned previously. Part of the problem is the credibility outside of this community that there really is a need for this type of data and we all ought to work hard at talking colleagues in other departments into doing experiments, in addition to measuring the ion molecule rate constants and geomeries. There are other astrophysically important experiments to be done, and I think once we get that message out, we might find the funding needed to address these problems a little easier to get, and also, some of the answers to the questions that we really are faced with done in a more realistic way. So it's part of our job, I think, to try to bring that message across. It's also part of our job to referee our work carefully so that it doesn't look like black magic.

LEGER: From the outside you see that many meteorites are iron. What criteria have we used to eliminate the possibility that iron isn't in the silicate? Is there any optical reason for discounting the possibility of metallic grains in the ISM?

Draine: There's no firm optical evidence, or at least I don't believe there's any firm optical evidence, against iron grains. One has a prejudice that one wants to put together enough silicates for the models, but that's more of a prejudice than a constraint.

Hecht: Joe Nuth and I (Hecht and Nuth, 1982, ApJ 258, 878) measured iron extinction in the lab and there were no optical properties up to 190 nm to distinguish, there was just a straight line. So, in principle, I guess iron could contribute.

ALLEN: One of my pet concerns is the issue of what is the composition of grain mantles. If one looks at the numbers, one finds out that molecular hydrogen can stick to silicate or ice grains. However, there's been this notion in the community for many years that the grain mantles are just basically nitrogen, oxygen, and carbon with hydrogens on them, rather than possibly a large fraction of molecular hydrogen composing the grain mantles. This latter possibility would have an impact on the grain physics. I would ask researchers to put an excess of hydrogen into their experimental mixture and to really see whether the hydrogen sticks along with everything else to some proportional extent or whether there is, in fact, a preferential sticking of the ices relative to the hydrogen so that we can really sort out the issue of what is the composition of the grain mantles in regions which are heavily depleted in volatiles.

HAGEN: One thing that I came here hoping to learn more on is just how dirty the silicate grains are. In a fairly optically thin dust shell, the amount of the emission you see is very much dependent on the dust temperature, and if you want to find out how much dust there is, you have to know what the dust temperature is, and to do that you have to know how dirty the grains are. Therefore, whether it's direct or indirect evidence on grain dirtiness, it would be extremely nice to have something.

Leger: A complementary question to that is how dirty a silicate has been made in the laboratory. For instance, if one wants to make a very dirty silicate, what is the maximum K that has been achieved in the laboratory?

Jones: Stick some carbon in it and you can make it as black as you want.

Stephens: Again, you have to define dirtiness, and at which wavelength.

Leger: It is that amount which is needed to match observations of radiation in the infrared around stars, say around 2 microns.

JONES: One of the things that came out in the joint interstellar/circumstellar session we had the other day was this question of whether or not there's evidence for the features we see in the diffuse interstellar medium (e.g., the 2175 bump, the 3.4 micron stretching and the infrared emission features we see in reflection nebulae), in the circumstellar regions. With the exception of the 2175A feature, which people have actually looked for, it's pretty obvious that we haven't really thought about it. I think that this is an important question, because when we look at planetary nebulae and see the IR emission features, it may have important implications, presumably it's the ejecta from the red giant phase. Yet, I don't know of anybody who's actually started looking at giants to see if we can find these features, particularly the 3.4 micron feature, in the circumstellar environment.

Hagen: There is a paper by George Wallerstein (Snow and Wallerstein [1972] PASP 84, 492) a few years back in the PASP where he looked for the diffuse IS bands around the red giants.

Jones: Yes, that's the diffuse interstellar bands in the visible and they are not found in circumstellar shells. I think it's important because if you cannot find those features in the circumstellar dust, then maybe that lends weight to this idea that it doesn't make any difference what the stars make initially because all CS dust gets reprocessed in the IS medium.

Stencel: Greg Seab and I once tried to use IUE data to look for the mid-UV bump, analogous to the 2175A feature, in some oxygen rich red giants. This was long enough ago that the data base was not adequate. The signal to noise was poor. Some suggestion that the bump moved to longer wavelengths was found, but that's the sort of thing that could be repeated now with the larger data base.

Jones: It bears directly on the question of grain destruction in the interstellar medium.

MARTIN: I, along with a lot of other people I'm sure, would like to know whether the 2175 angstrom feature is really an indicator of a large component of carbon bearing grains (since that's used as the main piece of evidence for those grains). A related question is that as far as I can see, the amount of carbon bearing grains in the IDP's is quite small. The question that arises from that is how are these carbon grains destroyed on their way to the protostellar nebulae if they are so prevalent in the IS medium.

HILDEBRAND: I'd like to know the strengths and detailed shapes of magnetic fields in molecular clouds and the mechanisms actually responsible for the magnetic alignment of dust grains.

GLASSGOLD: I'm concerned with CS dust, where the holy grail is to find out how the dust is formed, and the winds are generated. Since these answers won't be forthcoming so readily, I'd be pleased to learn something about the UV properties of the CS dust around evolved stars. This kind of information is critical for the further development of CS chemistry. The IS UV radiation field induces considerable chemistry in the outer regions of CSEs. Mike Jura and our collaborators have shown that it may be possible to obtain some information on the UV properties of the dust by studying the spatial variation of molecules, but direct determinations would be very valuable.

Hecht: You might look at Sitko, Savage, and Meade (1981 ApJ 246, 162) who did look at 10 or 12 circumstellar shells.

GRÜN: One question that's most important for me is the size distribution of interstellar grains, especially those close to the solar system. The reason for that is because there are forces in the solar system preventing the very small particles from entering the inner solar system. Only if there are particles in excess of a micron or so, will they reach one AU to be captured and brought back to the lab. If you don't have those large particles, then you may have to go out to about the distance of Jupiter or so in order to catch the incoming 0.1 micron size grains. This is not out of reach, but means that there are some constraints on the way we might catch IS material in the solar system.

Draine: May I ask what the dominant force is that prevents the 10 micron particles from reaching 1 AU?

Grun: It's radiation pressure, the pressure of the solar wind, and electromagnetic forces.

BUSECK: What sorts of mineralogical and crystallographic features would be of most interest to the astronomical community for us to look for in these particles? A related question is how useful would it be for us to do more work on things like the crystallinity of carbon, and how can this information best be transmitted to the astrophysics community?

Draine: All of our information about interstellar carbon grains come from optical observations, so if you can tell us things like how the dielectric function of polycrystalline carbon varies as a function of crystallite size, that would be very useful, particularly in the UV near the 2175 A feature.

Stencel: To briefly answer your operational question - it might be helpful for lab people to consider publishing very abbreviated, condensed summaries of large bits of work in the other journals. For example, you might condense a number of things, from say, the Journal of Chemical Physics into a single article in the Astrophysical Journal. In turn, perhaps astronomers could try to publish brief, problem-oriented reviews in JCP or elsewhere, so that people who don't have time to read the articles in the original journals would at least have an access point to the information.

Buseck: Would there be interest in such an article, and is it worth our while to try preparing it; would the ApJ actually accept this?

Stencel: I think if you collaborated with astronomers to make sure that the presentation was of direct interest, it might work.

Kerridge: Just a comment on that - most journals require the material to be new. If it's being published somewhere else, even if you sent it to some totally unrelated journal, then its still not new. So you might have a problem with that sort of policy.

Stencel: Maybe not if you accentuate the astrophysical application. An excellent example of this is a review of several years worth of measurements of molecular photodissociation rates with relation to the interstellar radiation field, by Long Lee, in the Astrophysical Journal, Vol. 282, p. 172 (1984).

LATTIMER: I would like to know more about the application of nucleation theory to some of the experiments on nucleation and also how much we really believe that nucleation experiments that are currently done in the lab have anything to do with what really goes on in circumstellar shells or around supernovae.

Nuth: Well, I can respond to part of that by saying that Bert Donn and I have just had a paper come out in the January 1985 ApJ and the conclusion of that paper was that nucleation theory has nothing at all to do with reality. Bruce Draine, on the other hand, feels that this represents a phenomenally strong viewpoint, and maybe I can agree with that sentiment to some degree. Maybe he wants to rebut our viewpoint.

Draine: I don't think there's anything to be gained by bringing it out here.

Lattimer: I didn't mean homogeneous nucleation theory, I meant it as a generic term to describe a process.

RIETMEIJER: I was pleased to learn that the 2175A feature is not, as I thought, fixed as a graphite feature but that it's basically an open field, and one I would like to work on. I feel that its very worthwhile for the meteorite and cosmic dust community to spend some time on this problem.

DRAINE: I would just like to repeat a bit of the question that Dr. Hagen brought up. I'd like to know more about what produces the absorptivity in silicaceous minerals in the 1-2 micron and visible region. For instance, cometary dust apparently has a very low albedo, as Dr. A'Hearn was telling us. What is it that produces the very high absorptivity? Is it carbon, is it some defect in the crystal structure?

Walker: It's not a crystal structure defect. I mean it's not color centers.

Draine: In lunar samples - what is the imaginary part of the dielectric function at one or two microns, and what is it that produces the high absorptivity?

Walker: Lunar samples are a special case. The opaque minerals in the case of the lunar samples are a poor analog to anything in the interstellar medium, they are titanium minerals. Lunar samples are very different from IS grains.

SEAB: Apart from wanting more information on just how grains were destroyed during grain-grain collisions, I would like to know more about the growth of grains in the interstellar medium. In particular, how do you grow refractory material, not only in the dark cloud phase, but also in the diffuse interstellar medium where you perhaps have a lot of atomic hydrogen. We've got some data that suggests that even for the outer parts of the diffuse clouds we've seen some grain growth effects, although there are some problems with interpretation. I'd like to see some more work done on that so that we can get a better idea of what to put into the theoretical models.

FRISCH: I think there are some problems with determinations of the gas phase abundances in diffuse clouds because the errors are huge. It is possible that a lot of material which appears to be missing from the gas phase might be contained in non-turbulent clouds with extremely narrow line widths such that the Doppler parameter is b<0.5 km/s. Blades et al. (1980, M.N.R.A.S., 193 849) have found, using very high resolution observations, that some diffuse clouds are non-turbulent. With actual Doppler values so low, gas phase column densities can be substantially underestimated when higher values are assumed in the analysis of the optical and ultraviolet absorption lines.

WHIPPLE: My question is prompted by a statement made on the first day that the amount of dust produced in carbon stars is equal to the amount produced in oxygen rich stars, even though carbon stars are less abundant. Is it possible that these stars are hiding in their own smoke screen?

Jura: Maybe I can comment on that. If you look optically at the sky, perhaps only at half a micron in our own galaxy, maybe only one-tenth of the number of the red giants are carbon rich. But if we look at the stars which are loosing a substantial amount of mass, on the order of half of them are carbon rich; and that's also true of planetary nebulae. So in some sense I think that many of the carbon stars are self-enshrouded, and I think that we know the answer to your question.

Unidentified: Let's not forget that every carbon star started its life as an oxygen-rich giant.

Jura: I'd just like to mention, in addition, that there are astrophysical environments, such as the Magellenic Clouds where the fraction of carbon stars is much higher. The reason we think that this happens is that the oxygen in these environments is much lower relative to hydrogen. For the first step in nuclear synthesis, hydrogen is connected to helium, and then to carbon, and that occurs in the center of the star and then comes up to the surface; it's easier for the carbon to become greater than oxygen if you start out with relatively little oxygen. Therefore, in the Magellenic Clouds, it's easier to find carbon stars than in our own galaxy, because these clouds were originally deficient in oxygen relative to the Milky Way.

WITT: I'd like to know more about the absorption and emission properties of very small particles (in the 10 angstrom size range or macro-molecules). We have now a rapidly growing volume of observations to indicate that particles of this type are present in a rather wide range of astrophysical environments, and in order to make quantitative determinations as to the importance of such particles (e.g., their relative numbers, etc.), and also in order to use them as probes for the physical conditions in those environments, it would be very valuable to have such information. I would imagine it could come best from laboratory work, and I look forward to seeing a lot more laboratory work in this direction.

WDOWIAK: I'd like to know a little bit more about the stability of some of these macromolecules outside of the dark clouds. In other words, are there more definitive rules about whether something will survive or not. There seems to be a gray area between something you know will definitely survive outside of the dark clouds (like graphite grains) and various simple molecules. Where is the cutoff, and are there any tricks for shielding, and so forth, where something might exist in one region and not in another. Spectroscopically you can probably match up any observed spectrum you want - there's enough molecules of sufficient variety. A more important question is whether or not the molecules are viable in the general interstellar medium. Dr. Leger introduced the problem a little bit earlier about the stability of molecular species and that's something that needs to be looked into a little more.

HAZELTON: This is a new area for me, but one of the questions that I haven't seen addressed here is what effect the clouds' plasma environment has on such things as nucleation and grain growth. In other words, if you have charged particles, is that going to change the dynamics of how grains grow and the crystal structure of the grains which you might expect from that process?

NUTH: What is the lower limit to the mass fraction of possible circumstellar isotopic anomalies that are needed at time zero in the presolar nebula to explain the meteoritic data? I'm really trying to get a handle on the minimum number of grains which must survive passage through the interstellar medium from specific circumstellar environments in order to explain the isotopic data. Of course, it would be very helpful if in a future version of the ion microprobe you could actually analyze 10-15 angstrom chunks of meteorite matrix for isotopic anomalies as opposed to melting the entire thing as is done right now.

Zinner: But there are too few atoms to measure in that small a sample.

R. Clayton: The question you asked cannot be answered in principle unless we know the isotopic composition of the grains that were out there initially. We can analyze the meteorites as well as you want, but it's almost hopeless since we don't know what the composition of the raw material was.

Nuth: But you may be able to put limits on the amount of material that was processed in the solar nebula. Say you figure that 50% of the material or more got processed in the solar nebula. If you see in the meteorites a fraction of the Neon-E that's ten percent of the total neon and if you then take a factor of 10 or something for processing efficiency, this would mean that about 1 or 2% of the original circumstellar material must have survived through the interstellar medium up to the time of the collapse of the protostellar nebula.

Kerridge: I think the problem is a good one, but it's impractical for this reason: we'd need to have a complete sampling of the presolar material, and I think rigorous quantitative answers are always going to fall down on these grounds.

Brownlee: It sure might shed a lot of light on this subject if we could recover some of the stuff that Mike A'Hearn talked about which might have been preserved at 30 K for eons in comets.

STENCEL: I thought it intellectually stimulating to consider the "hell and high water" that material had to go through from its point of origin around stars to get to the terrestrial microscope. Quite a few questions come out of that complete set of thoughts; however, I think the most applicable thing I will carry away is a test of the formation of grains around red giants, namely, radial and azimuthal variation in the 9.7 micron and other spectral features within extended chromospheres. That, in fact, came out of listening to discussions involving chemists.

HANNER: My first burning question has already been raised, namely what causes the comet grains to be so black - does that tell us anything about interstellar grains, or is it telling us something about solar system processing. So, my next question regards the silicates and what one can really learn from the infrared features about the nature of the silicates. Are the silicates in comet grains at all related to the silicates in the interstellar medium? Let me point out two things: (1) the 16-24 micron spectral region may be a lot more diagnostic for the kind of silicates than the 10 micron region. A lot more observations are needed there, particularly of comets. (2) when you have a comet that goes in fairly close to the sun, it's really doing a very nice experiment for you, by ramping the temperature of the dust. If one can observe the silicate features as a function of the comet's distance from the sun, then one is observing those features as a function of temperature, and perhaps one can learn something more about nature of the grains.

PUETTER: Well, what I'd really like to know is whether there's any graphite out there. We heard that the 2175A feature is really remarkable and people have often raised the question of does it really mean there's any graphite. I also heard something that I didn't know, and that is that graphite has an 800 angstrom feature. I was wondering whether people can look through the tails of comets with far UV techniques, or look at nearby stars and see any evidence for graphite. That's what I'd like to encourage, and if it's not possible, then I'd like to know if that's true.

A'Hearn: Looking through the tails of comets, or even through the coma of comets, has been proposed a number of times and attempted a number of times, and the problem is that the optical depth, even in the continuous absorption, is rather low. Therefore, finding enhancements in far UV extinction is pretty tough.

Puetter: So even where the features are, you don't find them. Does that tell you the answer?

A'Hearn: No, because the column density is too low.

Mathis: One idea was to use an HII region to serve as the diagnostic of what is going on at 800 angstroms, but unfortunately this graphite absorption at 800 angstrom mimics too closely that of hydrogen, even in the HII regions. It absorbs a fair amount of energy but doesn't change the ionization equilibrium so that you can't play the game of saying that I know what the ionizing source spectrum is; I look at the nebula and see what the ionization spectrum is, and I can tell what the ionized structure is, so I can tell what the absorption has to be. That does not work.

Puetter: So, basically you're saying that this cannot be done.

Mathis: The perfect theoretical prediction!

Hecht: Could you do it for quasars?

Puetter: It might be possible with the Space Telescope to get some more distant, more high redshift quasars. However, even the presence of the 2175A feature in quasars is extremely problemmatical, and if you found one with an 800A feature, I think that would be quite interesting. Also, there's another very significant problem and that is that once you start looking at high redshift QSO's you start finding hordes of Lyman alpha features in the intervening material, so that complicates things tremendously.

STEPHENS: I have a question which might relate to a number of different areas. One might be the relationship of one micron to 10 micron absorption of silicates, and the second is how much of a constraint does polarization data place on grain types. This is sort of a generic area of how do grains which may be of complex shape, perhaps having many phases in them, perhaps some of which are amorphous, how do these grains relate to a physicists grain, e.g., something that is spherical, has uniform dielectric properties, and is present in a very nicely separated size distribution. I think there is a certain amount of data that can be obtained which may break some of these constraints up.

Stencel: Could you elaborate?

Stephens: There are a number of things one can do. As a laboratory experimentalist, I think one possibility is to try to make grains in the various states, with multiple phases, and see if there is a unique signature for these sorts of grains; i.e., one makes a laboratory measurement of scattering phase function; absorption and albedo; is there a selection of these spheres that can mimic the optical properties of this collagulate or multiphase structure, or are there signatures that allow one to actually say "no these grains are not spherical" or "yes they are."

Hecht: If the 2175A feature is a graphite plasma resonance, (see for example, Huffman, 1977, Adv. Phys. 26 129) then shape effects will split that resonance. That's one way of telling that the grains have to be spherical, if the 2175A feature is a plasma resonance of graphite. If they weren't spherical, then you would have to have a split resonance.

WOOD: Several of the questions that concern me have already been asked, so I will say that I would like to know the extent to which physical effects, such as radiation pressure and gravitational instabilities cause local enhancements of the dust to gas ratio in the interstellar medium.

BROWNLEE: Of all of the particles that have been collected in the stratosphere, those which I personally think have the highest likelihood of being cometary, are the porous aggregates. They are carbon rich, are composed of anhydrous silicates, and contain no metallic iron at all. My question is, are most grains in the interplanetary medium anhydrous? And again, there is the question of metallic iron (almost all meteorites contain metallic iron - all chondrites contain metallic iron except for those that have been heavily altered). The main question is about the hydrated silicates, what evidence is there for or against hydrated silicates in the complex that the sun formed from, if not necessarily in the general interstellar medium itself.

Jones: What does water of hydration look like in a 0.1 micron grain? I know what it looks like on a surface, like on an asteroid, but would there be a diagnostic spectral signature in a grain?

Hecht: You would either have two water of hydration features or three, I would expect. You should have a 6.2 and a 3 point something, and if you believe the stuff that Ray Russell, John Stephens and I have gotten, then you may have another one near 7 microns (see Hecht et al, this volume). It seems like you should have at least a 6.2 and a 3 or a 3.1 micron infrared feature.

Jones: You see those in dark clouds, but you don't see them in the diffuse ISM.

Hecht: You don't see them in general?

Jones: You don't see water of hydration in the diffuse ISM, you can see ice in dark clouds, but you don't see ice in the diffuse ISM.

Hecht: Well, around W33A (in a dark cloud) you see that absorption at 6.0 microns, presumably due to water of hydration. You also see a 6.8 micron feature and the cause of that is controversial right now.

Brownlee: So the interstellar grains are expected to be anhydrous?

Hecht: Presumably, yes.

Kerridge: When you guys say water of hydration, do you actually mean H_2O molecules?

Hecht: No, we mean OH groups.

Kerridge: The hydrated silicates have OH groups.

Krätschmer: Hydrated silicates show an OH-feature at 2.7 micron which is very characteristic for any of these clay-type minerals (see e.g. Knacke and Kratschmer, Astron. Astrophys. 92, pp. 281-288, 1980). If you could find a 2.7 micron feature which is correlated with the 10 micron silicate band, this would strongly indicate the presence of hydrated silicate grains. However, the 2.7 micron OH band is very difficult to observe from the ground because of atmospheric absorptions."

SNOW: It seems to me that the material that exists on grain mantles has a strong likelihood of having an ultraviolet spectrum of some kind, and if so, this might be a relatively unexploited way of helping specify the composition of grain mantles. My question is what does the structure of the UV extinction curve have to tell us about the composition of grain mantles, and I think that there are two approaches to answering that. Anybody who has a candidate material in the laboratory and who is making spectroscopic measurements at other wavelengths, please try to find out what the UV spectrum is and get some idea of what the relative strengths of the ultraviolet features are. And for we who do ultraviolet observing, the challenge is to try to really find out whether there is structure in the UV extinction curve, apart from just the 2175 angstrom bump. That's a hard thing to do operationally but one can probably think of a way with the new technology that's coming. I'd like to see that exploited because I think it's got great potential.

MATHIS: I would dearly love to know how one can maintain two separate populations of grains, one of which is a good dielectric, and one of which provides a known amount of absorption in particular parts of the spectrum, if one in fact does maintain two separate populations of grains.

Hildebrand: The evidence you advance that you can't do it with one kind of grain is convincing, but it doesn't follow that there are two.

Mathis: At least more than one.

HOLLENBACH: I'm interested in the general question of the constraints on the amount of grain destruction in the interstellar medium, and there are two specific questions I'd like to ask. One is an observational question, namely, how much silicon is in silicates in different phases of the interstellar medium? The second part is to the people who do the meteoritic and cometary record. I've got a much better idea after this workshop, and perhaps things will get more quantitative in the future about the kind of constraints on the properties of the grains which are in the interstellar medium. In other words, constraints such as what fraction of interstellar dust must be condensed ejecta from supernovae or red giants, and what evidence do you have for the chemical composition and structure of the interstellar dust. And if you can identify the materials that are interstellar dust, is there any evidence they've been shocked processed, since we can predict that almost every grain has been through a fairly energetic shock? This means that the grains may have ions inplanted in them, they may be sputtered, and perhaps cratered by grain-grain collisions.

Leger: It may be that very small particles, even polyaromatic hydrocarbons came from grain-grain collisions in shocks. This might be a very powerful source for these molecules. The origin of these materials is completely open at this time.

Wdowiak: Presumably the interplanetary grains came through the bow shock of the earth on their way here. Can one see any evidence of that?

Jones: Well, is it really strong enough to do anything?

Hanner: It could have fragmented fluffy grains.

SILVERBERG: What do other galaxies, such as the Magellanic Clouds, tell us about grain formation?

DWEK: Does dust actually form in supernovae or is the IRAS data contaminated by line emission?

HAUSER: Is it possible to get to the point where we know enough to be able to remove the IR foreground so that we can study the cosmological IR background?

MARGOLIS: How do the thermodynamic conditions in the circumstellar environment (e.g., T, P, etc.) effect the final composition and structure of the materials delivered to the ISM? For example, how do novae produced grains differ from those produced in circumstellar shells?

R. CLAYTON: What really happens to silicates in the interim between formation in a circumstellar environment and incorporation in the most primitive interplanetary material (such as a chondrite matrix)?

KRATSCHMER: Can we do observations in "clean" astrophysical environments (where conditions such as the temperature and pressure are well specified) so that we can follow the progression of vapor to amorphous silicate to crystalline silicate?

KERRIDGE: Since the deuterium enrichment which is observed in meteorites is generally attributed to fractionation in the interstellar medium (via ion-molecule reactions), can one predict the degree of isotopic fractionation which might be present in other elements, such as carbon or nitrogen, which could accompany hydrogen?

Allen: The one problem in trying to look for unique relationships between D/H fractionation and $^{12}C/^{13}C$ fractionation is the fact that it is currently thought that these branching ratios between isotopes are a function of the detailed chemistry that a molecule undergoes. Since the fractionation that you have found in meteorites is an amalgam of all the interstellar molecules, you probably would at best get an average number. These observations might be confusing because you wouldn't necessarily see the tie-ins to molecular clouds. What you're seeing in meteorites is a big mush.

Kerridge: I realize that this is a real pitfall. I guess I'd still like to see it quantified.

Allamandola: There is a follow-on. Tielens, about 3 years ago, published an article (Astr. Astroph. 119, 177 [1983]) in which he calculated how the D would be enriched by grain surface reactions. There were some reactions that were assumed. Some rates were a little bit too high, but the basic problem was done correctly.

JURA: My specific question is "what is the carrier of the diffuse optical bands?" My general question is what is the physics of the complicated interaction between hydrodynamics, nucleation, and grain formation in the region of CS envelopes where that happens and where the matter gets accelerated to infinitity?

Wdowiak: I think that the carrier is carbon; whether it's in the linear molecules of Douglas, or in the PAH's, remains to be answered.

Jura: There are several ways to answer this question. I'm looking for a very specific explanation.

Wdowiak: I think it's either a linear molecule, perhaps about 6 or 7 carbons long, or it's a PAH.

Hecht: It doesn't have to be only one molecule, there could be many.

Wdowiak: I agree, Dr. Kratschmer has made a carbon molecule that we think is probably a good candidate for the 4430 band (Kratschmer et al, 1985, to be published in Surf Sci.).

Snow: If you are talking about specific molecules as the source of these bands, and we can't even find C3 or C5, then you are talking about very serious abundance and stability constraints.

Wdowiak: That was the basis of the question I asked earlier. I'd like to know about the stability of small molecules. How small can you have something and have it be stable in the ISM?

Snow: I'd rather have very small pieces of graphite, at least they might be stable.

Wdowiak: I think it's either one or the other, they're both electron boxes to me, and it doesn't matter whether they're linear or whether they're aromatic.

Léger: I agree that there are two main constraints. They should be stable in the UV field of the diffuse medium and should be quite abundant. We think we have a general statement that any molecule with less than 15 atoms would be very efficiently disassociated in such a field, so I think we have now some constraint. It has to be a large molecule.

Kratschmer: But the most important constraint is that it has to fit the interstellar bands!

Mathis: And what scares me about making it out of common molecules is that they always have UV absorption. Molecular absorption has structure in it, and real UV extinction does not have structure in it, and the bump is not correlated very well with the diffuse interstellar bands. I'm very nervous about having molecules make the bands, because you can't turn off the absorption where you don't want it.

Léger: Something that may help you is that the transitions are sharper in the visible than they are in the UV. So we are not expecting to see very sharp transitions in the UV.

Mathis: But why don't you get a good correlation between the diffuse bands and the 2175A bump?

Léger: Such correlations would mean that all the bands came from those particular molecules, and nobody has ever said that. It may be only a minor contribution. There's one thing that is very interesting. If you look at the small Magellanic Cloud, it has very little free carbon in the diffuse medium. We now have weak evidence that there are no diffuse bands in the two stars which we have observed there to date.

Snow: I've made a lot of speeches about structure in the UV extinction curve. The problem is it's very difficult to do with present technology for two reasons. One is that the diffuse bands in the optical only start showing up at significant optical depths. You have to have a color excess of 0.5 magnitude or more, and because the general level of UV extinction is so high, that means there are very, very few stars with UV fluxes seen through sufficient column density that you would expect to see diffuse features in the UV. That's the problem we hope that progress will be made on using Space Telescope. The other problem is not one that's as easy to get away from, and that is that the hot stars have lines in the UV. They are not good continuum sources, there are lines everywhere, it's like trying to use an M star or pair of M stars to look for features. There is a lot of noise due to mismatching stellar absorption lines all through the UV. There's no good way around that, that I can see, except to get heavily enough reddened lines of sight so that the few features that may be there show up despite the noise. Due to these uncertainties, I can't rule out that there are diffuse bands in the UV based on present evidence.

Allamandola: A final comment on that is that it might be really helpful if it is possible to see what kind of correlations there are among the bands themselves. I know if you see one you see them all, but when talking about families of molecules, you might see three bands going together and that will really be a clue.

Snow: That's been done to a certain extent already but, of course, most of what's been done is photographic, often taking spectra from different sources, etc. It might be time to try that again in a more systematic way. I think that's a fair point.

D. CLAYTON: I am most curious at the present time about the extent to which isotopic and chemical fractionation patterns that are found in meteorites have correspondence in isotopic and chemical fractionation in the interstellar medium. I would like to know whether the excess magnesium 26 found in the aluminum rich minerals in the meteorites are there because the aluminum is alive in that mineral in that meteorite, or if it's a fossil. I would like to know what it is that's carrying excess oxygen 16 in the interstellar mechanism.

I would like to know if silicon and iron are together or fractionated from one another in the interstellar medium. I think it's important for so many things. Silicon and iron are fractionated in meteorites, and if some chondrites have higher ratios of silicate to iron than others, is there any correspondence to the pre-solar conditions? Another example of that kind is the tendency of iron to go with sulfide, does this come about because iron is associated from the beginning with sulfides in metal in the interstellar medium, or is that something that's established strictly in the solar system itself from amorphous grains?

ZINNER: It seems that different people mean different things when they talk about grains. Interstellar grains are considered to be tiny grains on the order of 50 to 100 A in size, while when I think about a grain, I think about something like 10 microns or so, because that's what we can see in the laboratory. It's not clear that there is actually a connection between these two regimes. Eberhard Grun has already asked "what is the chance that we have interstellar grains of the size of 10 microns or so." This is, of course, very important because, if there are, then we can get a chance to eventually measure those that come into the solar system. But I think it's also important to ask whether if grains of that size exist in the interstellar medium or in dense molecular clouds before the formation of the solar system, did any of those grains actually survive? We talk about interstellar grains in meteorites, but what most of us mean is material which is isotopically different in composition, but is this material in the form of actual grains which existed previously? Lots of these isotopic anomalies are found in refractory phases, and one of the arguments that refractory elements are in the form of grains in the interstellar medium is the depletion of these elements, but does it mean that these grains actually survived as grains or have all the minerals which we find in meteorites been formed in the solar system?

Stencel: One data point, of course, is that IRAS photometry suggests the Vega and the Beta Pictoris systems contain these and larger grains.

Jones: I remember from the discussion we had in the interstellar medium group. There's not enough mass left to make a lot of big grains. If you took all the mass that was left and put it into big grains you would have very few. You wouldn't be able to see them. So I don't see how we're ever going to see them by spectroscopic or photometric techniques in the general interstellar medium, it's just not possible.

Snow: Well, how much slop do you need, I mean, I think those arguments are based on depletions, right?

Jones: I just repeated what I had heard going around.

Snow: Yes, I know, and it has been stated rather dogmatically before. It seems to me there's an awful lot of uncertainty in just what fraction of the mass could actually not be in the gas. I mean it's certainly $\pm$ 10% and probably is larger than that. There could be some large grains there even if they aren't the dominant size.

Jones: But can we find 10 micron grains?

Mathis: Yes, the real fundamental physics puts in some constraints from the Kramers-Kronig relationship. In order to get the total amount of extinction that you see already, you need to have practically all of the heavy elements (with the exception of nitrogen and oxygen) in the grains which produce extinction and these elements must be distributed in the best possible way. The reason MRN came about was to put the grains in the most efficient possible absorbing mode. That's a very fundamental relationship, so there can't possibly be much mass in grains that you don't see. On the other hand, no one can say that there aren't any large grains. In fact, I assume there are, but you cannot possibly say that all, or even a significant fraction, of the interplanetary grains were that big in the first place. Fundamental physics enters that stage, not just a model.

MENDIS: It has been an article of faith that cometary particles are very fragile. I think that it is time to quantify this and put limits on the strength of the grains. Much of this comes from studies of the pseudo-synchronic bands that are seen down the tails of comets and especially Comet West. The numbers quoted are on the order of 10^4 dynes/cm^2. Since Brownlee particles are touted as being cometary particles, it would be nice if we could make some measurements of the strengths of these particles. Admittedly, there will be some selection effects, since stronger particles will be preferentially collected, but I still think such an effort would be worthwhile.

WALKER: The question I have is "how can I recognize an interstellar grain when I see one?" It stems from the fact that when I look at the meteorite matrices, I don't see anything that looks like the interstellar grains that have been described to me by Mayo Greenberg and my colleagues here; namely little refractory cores which are highly asymmetric in order to account for polarization, etc. I've looked for interstellar grains as I have heard them described by astronomers, and I don't see them. Now maybe that's because I have the wrong preconceptions, but there are some things that I would like the astronomers to tell me which touch on this issue. For example, the composition of the grains, not only those that you've seen, obviously there are some silicates, but the possible compositions that could occur because of the depletions, things that may not be seen, but may be there and that one can infer because of these depletions. And the correlation of the composition with other properties, specifically

correlation with isotopic properties. For example, is the 2175 A band found in the same region in which the C12 to C13 ratio has been determined very precisely as 45? Is this the region with a great deal of polarization? In what wavelength band is this polarization? Can you tell me something not only about whether the carbon is there and the isotopic signatures are there, but also can you tell me something about the shape? I think, by the way, that it's a two-way street, that one can look at the meteorites and find certain things and perhaps ask the related question whether there's any evidence for those same things in space or whether the evidence precludes their existence. What is perhaps a red herring is the fact that we have the carbonates in the interplanetary dust particles, and it has a 6.8 micron band. Maybe that doesn't have anything to do with the interstellar clouds, but it's interesting to note there is a 6.8 micron feature there. What about hibonites which are found in mateorites? It's a titanium, calcium rich refractory mineral and a big carrier of titanium anomalies. Ernst has just found one with a 10% excess of titanium 50. Would hibonites show up if they were in the interstellar medium? Is this a refractory phase that's partly responsible for the depletions in the ISM or not? What can you tell us about that? There must be a better way of correlating the information that exists and gives a better answer than is currently available to the question "how do I recognize an interstellar grain when I see one?"

Mathis: Well, with regard to your question on polarization and what kind of grain shape does it give, the answer is that the empirical law of polarization can be fitted in a variety of ways and one parameter is just how big the particles of that distribution are. What we call big particles (tiny ones to you; that is around 2/10 or 3/10 of a micron) are important, since by fiddling around with those you can change the shape of the polarization, and with a simple power law distribution and absolute cut-off, you in fact derive the average polarization curve very well. So I think what you're looking at from the polarization shape is the size distribution which is not what you are so interested in.

Walker: By the way, it's true that for isotopic measurements you need grains as large as 10 microns. It's not true that you need 10 micron grains in order to make observations that are relevant. The transmission electron microscope works on the scale of angstroms and gives you detailed morphology, shapes, and compositions. That's a way that we can look at grains that we think are primitive and possibly obtain size distributions.

Brownlee: I think there's a misconception about grain sizes in meteorites. Most of the interplanetary dust particles are less than 1000A in size. Although most work on interplanetary dust is done on large particles, this is simply because those are the ones that we can handle in the laboratory.

Hecht: Almost every material that I know of, somewhere from the UV (say around 1000 angstroms) to the Far IR, contains some characteristic features, either IR absorption features, emission features, or UV bands in the case of metallic grains. There are precious few astronomical observations in which these features are seen. One would expect that a majority of grains have to fit those observational constraints. So you may have small quantities of the platinum or iridium grains, but it seems unlikely that you could have large quantities of exotic materials that have distinct emission features, otherwise you'd see some evidence for this.

Dwek: Is there anything known about the optical constants for calcium or titanium rich crystals and things like that so that people can model double layered silicates that have these things in them by Mie theory in order to see whether we can rule them out on some grounds?

Hecht: Huffman did a section on minerals in his review paper (1977, Adv. Phys, 26, 129).

Dwek: Did he talk about calcium and titanium oxides? Because we are talking about two different types of things. Astronomers are interested in the bulk grain composition, whereas, meteoriticists are interested in the rarer elements which might be just "dirt" in silicates.

Hecht: If you're talking about calcium oxide and things like that, those would have specific signatures, but if they are buried in the middle of silicates they might not be observable. I'll have to ask Joe to make it and measure it.

Hildebrand: It is possible to tell something about the shape of silicate grains, at least in principle. Bruce Draine has shown that if you compare the wavelength of maximum absorption with that of maximum polarization you get information on whether the grain is oblate or prolate, and there are other ways to do it.

Walker: And what does the grain look like?

Hildebrand: From polarimetry near 10 microns Draine and Lee (ApJ 285, 89 [1984]) argue that the silicate grains are oblate. I think their arguement is correct in principle, but it is based on the results of difficult measurements. From a comparison of 10 and 20 micron polarimetry, I would infer that they are prolate. It is an open question on which we can expect new measurements and further analysis.

Brownlee: About that question on the shape of the grains. When you talk about prolate grains do you really mean prolate grains or just two round grains stuck together? Are most grains aggregates of other grains? The easiest way to form elongated grains is by aggregation.

Hecht: I think in principle, optically one should be able to distinguish between a prolate grain and two round grains stuck together. One may have different dipole-dipole interactions, for example. Two grains stuck together have dipole-dipole interactions, whereas, a prolate grain acts differently. But it's not an easy problem at all.

Stencel: Not being an easy problem summarizes the whole field; we will adjourn on that note for the open-ended coffee break!

Ionized Polycyclic Aromatic Hydrocarbons in Space

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The mid-infrared spectrum of a continuously increasing number of stellar objects, planetary and reflection nebulae, H-II regions and extragalactic sources show a distinctive set of broad emission features at 3.3, 3.4, 6.2, 7.7, 8.6, and 11.3 um known collectively as the unidentified infrared emission bands. Although discovered in 1973, identifying the band carrier and elucidating the emission mechanism have been elusive. To date the following models have been suggested to account for the observations: 1) IR fluorescent emission from UV excited molecules on 0.1 um radius grains, 2) IR thermal emission from smaller, 0.01 um grains, and 3) non-equilibrium thermal emission from even smaller 0.001 um grains. All suffer limitations, the first requires a multicomponent mantle composition largely independent of local conditions, the second unusually high values for the infrared oscsillator strength and the third relies on the questionable assumption that a 10A sized species can be treated as having bulk thermal properties. Recently, Leger and Puget (1984) proposed that the emission originates in neutral polycyclic aromatic hydrocarbons (PAHs) and used a bulk thermal model to calculate the predicted emission spectrum expected from coronene, which has been "heated" by the absorption of a single photon.

In this poster a model is summarized in which the bands arise, not from grains, or neutral molecules, but from positively charged PAH's on the basis of their low ionization potential and the excellent agreement between the emission bands and laboratory spectra of auto exhaust which contains these types of molecules. These are excited by the absorption of individual U.V. photons, and infrared emission follows as these highly vibrationally excited molecules relax by infrared fluorescence. The emission mechanism must be treated explicitly, taking the statistical nature of the emission process fully into account because each highly vibrationally excited molecule contains a limited number of oscillators with distinct frequencies. This picture, while obviating the need to involve grains or neutral molecules at all, can account for the band intensities, positions and shapes.

The suggested presence of "small" ring containing molecules in space is controversial, and this suggestion has serious ramifications for other spectral regions as well, ranging from the infrared cirrus discovered by IRAS to the classic problem of the diffuse interstellar absorption bands (DIB's) in the visible. Although discovered about 70 years ago, the carrier of the DIB's remains unknown. The interstellar origin of these bands was established in the 1930's when it was shown that the strength of the features did not depend on stellar type, but rather on the amount of extinction, or reddening, toward each star. As the reddening is caused by the intervening gas and dust,

the carrier of the DIB's must be associated with this material. Equally strong cases can be made for a gas phase as well as a solid state origin, but neither explanation is completely adequate. An origin in, or on, the dust implies an asymmetry of the bands which is not observed while a gas phase origin requires large molecules to produce broad bands, yet the presence of large molecules in the harsh interstellar environment seemed impossible. Thus, although an enormous effort has been made observationally, experimentally and theoretically to understand this phenomenon, identifying the carrier of the DIB's has become a classic problem in modern astronomy.

The proposed presence of PAH's in such a variety of objects points to their ubiquitous presence in the interstellar medium. Based on this, we suggest that PAH's are responsible for the DIB's. As pointed out, the interstellar UV field will ionize many of these molecules, changing their electronic structure into that of a radical, which will absorb at discrete wavelengths in the visible. Out of a previously published collection of solid state PAH radical cation spectra we select five on the basis of the unique thermodynamic stability of their carrier and compare them directly to the wavelengths of the DIB's. Although the match seems quite favorable, strongly suggesting that PAH radicals are the long sought after carrier of the DIB's, much laboratory work must be done to test this hypothesis.

"CLEAN" VS. "DIRTY" SILICATE GRAINS AND THE STATE OF CARBON CRYSTALLIZATION IN INTERSTELLAR AND CIRCUMSTELLAR DUST

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The 9.7μm spectral feature of interstellar dust has commonly been ascribed to rock-forming silicates such as olivine [$(Mg,Fe)_2SiO_4$] and enstatite pyroxene [$(Mg,Fe)SiO_3$]. However, it only approximately matches their spectra. To explain the distinction, astronomers refer to "dirty" silicates, although the meaning of this term is left vague. A common explanation is that these minerals are "disordered", but without specifying what is meant. However, terrestrial, meteoritic, and interplanetary olivine and enstatite are well ordered (aside from the Mg-Fe disorder that is typical of these minerals) and, moreover, there are no likely crystal-chemical ways in which they could disorder. We have used electron diffraction to study many interplanetary dust particles that contain olivine and pyroxene (e.g., Tomeoka and Buseck, 1984), and in none of them have we detected any sorts of anomalous disorder. It is not at all apparent what sorts of "disorder" could account for the "dirty" silicates in the interstellar dust. It thus behooves astronomers to attempt to specify more clearly what sorts of silicates, if indeed they are silicates, are indicated by the 9.7 μm spectral feature. Terminology as used at present is not compatible with standard mineralogical usage.

In another part of the spectrum, the 2175 Å spectral "bump" appears to be ubiquitous for interstellar dusts. It is commonly assigned to amorphous graphite or some similar material, although concerns have been expressed that the wavelength of the bump should shift slightly depending on grain size, and such shifts in position have not been observed (e.g., Mathis, 1985). Recently, results have been obtained of high-resolution transmission electron microscopy of both natural carbonaceous materials and organic molecules that have been heated and carbonized in the laboratory under controlled conditions (Buseck and Huang, 1985a,b). These results indicate that there are a wide range of recognizable stages during the transition from totally disorganized and amorphous carbon to good crystalline graphite.

Degree of polymerization into individual sub-planar and then planar polycyclic aromatic sheets of hydrocarbons grade into poorly stacked sets of sheets full of many edge dislocations and bonding vacancies. These, in turn, grade into the regularly stacked and laterally extensive sheets that characterize graphite. Work is required to determine whether these steps each have their own IR and UV signatures and how they may relate to the 2175 A bump. In the meantime, however, it is important to be aware that the crystallization of carbon to graphite is complex and that it would be desirable to specify the state of crystallization in the interstellar medium more precisely than just whether or not it is "amorphous".

Buseck, P. R. and Huang, B.-J. (1985a) Conversion of carbonaceous material to graphite during metamorphism. Geochim. Cosmochim. Acta, in press.

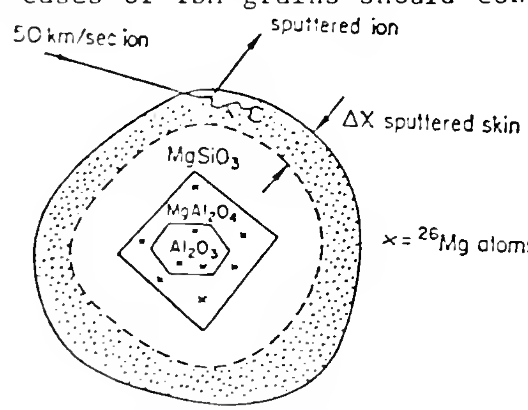
Buseck, P. R. and Huang, B.-J. (1985b) An electron-microscope investigation of the structures of annealed carbons. In prep.

Mathis, J. S., 1985, Observations and theories of interstellar dust. Proceedings, p. 8, NASA Workshop on the Inter-relationships Among Circumstellar, Interstellar and Interplanetary Dust Grains, Aspen Institute, Wye, Maryland.

Tomeoka, K. and Buseck, P. R., 1984, Earth Planet. Sci. Lett. 69, 243-254.

EXCESS DEPLETION OF Al, Ca, Ti FROM INTERSTELLAR GAS. Donald D. Clayton, Rice University. Although data is somewhat variable, it does not appear distorted by the following statement: the fraction of interstellar Mg or Si (typical refractory elements) residing in the gas phase is at least ten times greater than the fraction of Al or Ca (superrefractory elements) residing in the gas phase. This seems inexplicable by thermal condensation because all of these elements eventually condense in a thermal cooling gas unless the condensation sequence is artificially terminated immediately after the condensation of Ca. It also seems inexplicable by cold sticking because it requires Ca to stick ten times more efficiently than does Mg. It also seems inexplicable because sputtering by interstellar shock waves should vaporize surface Ca as efficiently as it does surface Mg.

A self-consistent explanation seems possible by combining these ideas with a chemical memory of the condensation sequence. Because Al_2O_3 condenses prior to $MgSiO_3$, for example, the refractory cases of ISM grains should contain Al-rich cores surrounded by $MgSiO_3$ mantles, as illustrated in the figure, taken from Clayton (1982, Q. J. Roy. Astron. Soc. 23, 174). As a result, interstellar shocks must sputter away the entire $MgSiO_3$ mantle (as well as any overlying cold-accreted mantle) before sputtering the Al. The grain must be completely destroyed before the Al is even touched. It therefore becomes important in the construction of cyclical histories for ISM grains to distinguish between sputtering that only removes 90% of a grain and sputtering that totally destroys each grain core (a much more restrictive condition). The same argument applies to Ca and Ti because those elements, like Al, take up initial residence within the superrefractory cores.



Because of this shielding against sputtering, it appears that incorporation into stars (astration) is the major destruction mechanism for superrefractory cores, even if sputtering is the major mechanism for converting dust mass into gaseous mass. To retain the preferential depletion of Al, therefore, it appears necessary and sufficient that in all subsequent mass loss the Al must again recondense primarily into refractory cores of grains. That is, Al is so depleted because it is not ejected in gaseous form from stars except with very low efficiency. In the useful nomenclature SUNOCON ≡ supernova condensate (thermal) and STARDUST ≡ stellar thermal condensate, we would say that freshly synthesized Al first appears in SUNOCON cores and astrated Al is reinjected in STARDUST cores (Clayton 1978, Moon and Planets 19, 109).

The importance of this extra depletion of Al and Ca thus becomes its indicator of the structural history of the refractory parts of interstellar grains. What is now needed is detailed numerical modelling of the total chemical history in coordination with details of observed depletion patterns.

PREGRAPHITIC MOLECULES AND THE RED-RECTANGLE EMISSION

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The Red-Rectangle (AFGL 918) nebula emission has several components:

(1) Emissions and absorptions characteristic of a H^+ region.

(2) Blue dominated light scattered from the illuminating star.

(3) A large and broad emission bump in the red part of the spectrum that gives the red aspect of the nebula.

(4) Narrower emission bands superimposed on feature (3).

(5) IR emission bands at 3.3 - 6.2 - 7.7 - 8.6 and 11.3 µm.

In light of the recent identification of component (5) as emission from pre-graphitic molecules (Léger and Puget 1984), we investigate the possibility that component (3) is luminescence from the same molecules.

The broadness of this bump prevents a definite spectroscopical identification with any species. However, its wavelengths are typical of *phosphorescence from large pregraphitic molecules*.

An important argument is the estimate of the needed *abundance* and *luminescence yield* of the carrier. Considering the luminosity of the illuminating star, that of the nebula, its optical depth... it is found that, with a luminescence yield of 25% in energy, the *species responsible has to be responsible for ~ 10% of the absorption in the UV* by the nebula material. The pregraphitic molecules can fulfull those requirements, for instance, the phosphorescence quantum yield of hexabenzocoronen is ~ 40% (Schmidt, 1985). For the abundance, they are among the very few species which are at that level : 10% of the dust mass and 30% of the 2200 Å absorption, as estimated in the IRAS Cirrus.

USING THIN CIRCUMSTELLAR DUST SHELLS TO STUDY SILICATE GRAIN OPACITIES. Wendy Hagen, University of New Mexico. Among M giants and supergiants with silicate emission features, a variation in the shape of the emission feature is seen from star to star. Dust shell model calculations show that these differences cannot be explained entirely by reasonable differences in dust density distribution or shell geometry. In an optically thin dust shell, emission is porportional to $Q_{abs}(\lambda)\ B_{\lambda}(T)$, and the estimation of dust opacity can be done more accurately than for dustier stars for which radiative transfer effects become important. The observed silicate features for a sample of M giants and supergiants will be presented, along with probable variation of Q_{abs} over the observable 10-micron feature. Constraints on the long-wavelength dust opacities determined from the IRAS observations will also be presented.

IUE AND IRAS OBSERVATIONS OF LUMINOUS M STARS WITH VARYING GAS-TO-DUST RATIOS. Wendy Hagen, University of New Mexico; Kenneth G. Carpenter, JILA; and Robert E. Stencel, NASA HQ. Previous work on circumstellar gas and dust surrounding M giants and supergiants (with sufficiently thin dust shells that the spectra in the blue can be observed at high resolution) has shown the stars to split into two distinct classes (Hagen, Stencel and Dickinson, 1983, Ap. J. 274, 286). Stars with a high gas-to-dust ratio all show chromospheric Ca II H and K emission. Stars with a high dust-to-gas ratio do not show chromospheric Ca II emission but are the only ones to show Balmer emission indicative of atmospheric shocks and are also the only ones to show maser emission. In order to determine whether all chromospheric indicators disappear in high dust-to-gas ratio stars, we are conducting a survey of stars in both of these classes with the IUE satellite. Our initial low-resolution observations of the 2200-3200A spectral region of a limited number of stars reveal 2800A Mg II emission in all the observed stars regardless of the dust-to-gas ratio. In addition, very deep exposures of three dusty stars show Fe II, Al II and perhaps Mg I emission, and one of the three (TW Peg) even appears to show C II (UV 0.01) emission near 2325A. These lines are usually associated with chromospheres in late-type evolved stars. Although there is some overlap, the dusty stars tend to have higher ratios of flux in the Fe and Al lines to the flux in the Mg lines. This could be a result of the Mg II line (with its similar atomic structure to that of Ca II H and K) flux being reduced by the same process which inhibits Ca emission. Mg may not be as significant a radiative loss channel for the chromospheres of cool, dusty stars.

The long-wavelength infrared fluxes for the program stars were obtained from the IRAS point source catalog. In general the long-wavelength fluxes were consistent with the silicate emission seen in previous observations of the 10-micron feature. Stars with no observable 10-micron dust emission show a black-body distribution of the longer-wavelength flux. There is no obvious difference in the long-wavelength observations between the two groups of stars; the long-wavelength excess tends to follow the 10-micron excess and not the dust-to-gas ratio. Comparisons of the IRAS observations with dust shell model claculations will be presented.

The Nature of Cometary Grains from Remote Sensing

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Our knowledge of the physical properties of cometary grains derives primarily from measurements of their thermal emission and optical scattering. These results are consistent with the properties of micrometeorites collected in the stratosphere (Brownlee particles).

1. The scattered light at λ 1-2 μm is neutral or somewhat red. The lack of Rayleigh scattering => grain diameter $\gtrsim \lambda$.

2. Thermal emission spectra indicate grain temperatures higher than a theoretical black body in equilibrium => grains composed of absorbing material and grain size < 10 μm.

3. Emission features near 10 μm and 18 μm => small silicate grains present.

4. Ratio of scattered/thermal radiation => grains very dark; geometric albedo $A_p \approx 0.015 - 0.04$ at λ 1.2 - 2.2 μm, comparable to the rings of Uranus.

5. Analysis of particle trajectories in dust tails => $\beta_{max} \sim 2.5$ and ~ 0.5, typical of small absorbing and dielectric (silicate) particles, respectively.

6. Icy grains (H_2O) are probably present in the coma of new comets at large heliocentric distance (3 μm feature seen in Cernis; large OH production in Bowell), but not generally in comets within ~ 2 AU of the sun.

7. Three comet nuclei have now been detected in the thermal infrared (IRAS-Araki-Alcock; Neujmin 1; Arend-Rigaux), with T ~ 300 K and $A_p < .05$ => some "old" comet nuclei have a dark, nonvolatile surface.

An Experimental Study of Plasma Grain Interactions

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Dust grains occur throughout the universe in many systems such as protostellar dust clouds, planetary ring structures and in a near earth environment as the result of man's activities. These grains interact with the local plasma and radiation environment and this interaction certainly influences the evolution of the dust grains. In the present work, an initial, experimental effort has been made to study the interaction of bismuth dust particles with a background plasma.

The approach developed was to pass a beam of bismuth particles through a plasma and detect the charge accumulated on the particles emerging from the plasma using a retarding potential analyzer. The experiment is therefore defined by three specific functions:

1. Production of the beam.
2. Production and diagnosis of the plasma.
3. Detection and analysis of beam charging.

The beam was produced by melting bismuth in a moderate pressure oven (20 - 100 Torr), condensing particles in a cooled chamber and accelerating the particles through differentially pumped orifices into the main vacuum chamber.

The plasma is produced by a hot cathode discharge in a background of 1 - 10 x 10^{-4} Torr of argon. The plasma parameters are determined with a Langmuir probe and a retarding potential analyzer.

The charged beam is diagnosed with a retarding potential analyzer. Because of the large background flux of electrons from the plasma, phase sensitive detection techniques are required. This was achieved by physically chopping the beam and measuring the output of the RPA with a lockin amplifier. Measurements indicate the existence of two distinct, modulated signals. The first is due to the beam of charged bismuth particles while the second is due to modulated electrons emerging from the plasma.

RPA curves of the bismuth beam provide a measure of the relative charging rate of the particles as a function of particle size and velocity and plasma density and temperature. Analysis of the RPA curves indicates a good correlation of the data with simple theory based upon independent measurements of particle size distributions, particle velocity and plasma parameters.

The modulated electrons are produced by the perturbation of the background electron density and plasma potential. Therefore, analysis of these curves is expected to provide a measure of the perturbation of the plasma parameters for comparison with theory.

A new direction is now being taken to measure the interaction of positively and negatively charged particles in order to determine the effect of charging on coalescence of particles. In order to accomplish this, two beams will be produced, with one charged negatively by a low energy electron beam and one charged positively by uv radiation. These beams will be collided at 90° and coalesced particles will be detected along the midline between the beams using laser scattering techniques.

SIMULATION OF COSMIC DUST SPECTRA. J. H. Hecht[a], R. W. Russell[a], J. R. Stephens[b], and P. Grieve[a]. A helium-cooled circular variable filter ($R \sim 50$) spectrometer has been constructed and is being used in a program to measure emissivities from 4-14 μm of possible astronomical and cometary dust material. The first material measured was an amorphous Mg-poor silicate supplied by NASA/GSFC[1]. The sample showed a strong feature at 9.2 μm, plus very weak features near 11.3, & 12.4 μm typical of a predominantly Si_2O_3 and amorphous quartz mixture[1]. Two features appeared at 6.2 and 6.9 μm with a relative strength of a quarter of the 9.2 μm peak. Upon exposure to saturated water vapor the relative strength of the 6.2 and 6.9 μm peaks increased compared to that of the 9.2 μm peak. Subsequent heating to over 300°C did not significantly decrease either the 6.2 or the 6.9 μm feature even though the spectral shape in the 8-14 μm region indicated that the dust changed to amorphous quartz (SiO_2). While quartz and crystalline Mg silicates are not known to have 6-7 μm features, some amorphous silicates have been shown to have transmission or emission features in the 6-7 μm wavelength range[2,3,6,7]. These peaks are tentatively identified with H_2O which persists in the lattice at least up to 300°C. While these features may match those seen in spectra of astronomical nebulae[4,5], a more likely occurrence may be in H_2O-rich cometary silicate grains such as those associated with Comet Halley.

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LABORATORY STUDIES OF THE INFRARED SMALL-PARTICLE EXTINCTION OF AMORPHOUS SILICATES

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The broad interstellar IR extinction features located at 9.7 and 18 um wavelength are believed to originate from silicate dust grains. Cosmic abundances suggest that the silicate should have a chemical composition similar to that of olivine, i.e. $(Mg,Fe)_2 SiO_4$. Olivine is a very common terrestrial silicate mineral of crystalline structure. However, crystalline olivine grains do not fit the interstellar features well. Based on spectroscopic data obtained in laboratory studies and astronomical observations it has been concluded that the interstellar silicate grains consist of a material with amorphous rather than crystalline structure (see e.g. Aitken, 1981, and the references therein). In the following, I want to review briefly the astronomical arguments and the results obtained in our laboratory experiments which support this view.

To appreciate the significant difference between the small particle extinctions of a crystalline and an amorphous silicate, fig. 1 shows both kinds of extinction spectra for a silicate of the composition $Mg_{1.9} Fe_{0.1} SiO_4$. Notice that the extinction is plotted on a logarithmic scale. The spectra were calculated using the published optical constants of both kinds of silicates (Huffman, 1977; Krätschmer, 1980), assuming that the dust grains are spherical in shape and of sizes small compared to the wavelength. The extinction of the amorphous silicate is characterized by (a) loss of structure within the peaks and broadening of the peaks, (b) decrease of strength in the extinction peak maxima, and (c) shifts of the peak centers to slightly shorter wavelength. All these characteristics also seem to be exhibited by interstellar silicates. The wavelength positions of the extinction maxima of the amorphous silicate (9.7 and 17 um) compare favourably with that of the interstellar features. The strength of the interstellar extinction at 9.7 um has been estimated to about 3000 cm^{-1} which, as a peak absorption, is unusually small for crystalline silicates (see e.g. Capps and Knacke, 1976), and is even lower than that of our amorphous olivine. The most powerful argument in favour of amorphous interstellar silicates is based on the apparent absence of any sub-structure within the interstellar 9.7 um band. The sub-features originate from the optical anisotropy of the silicates and are tied to the crystalline structure.

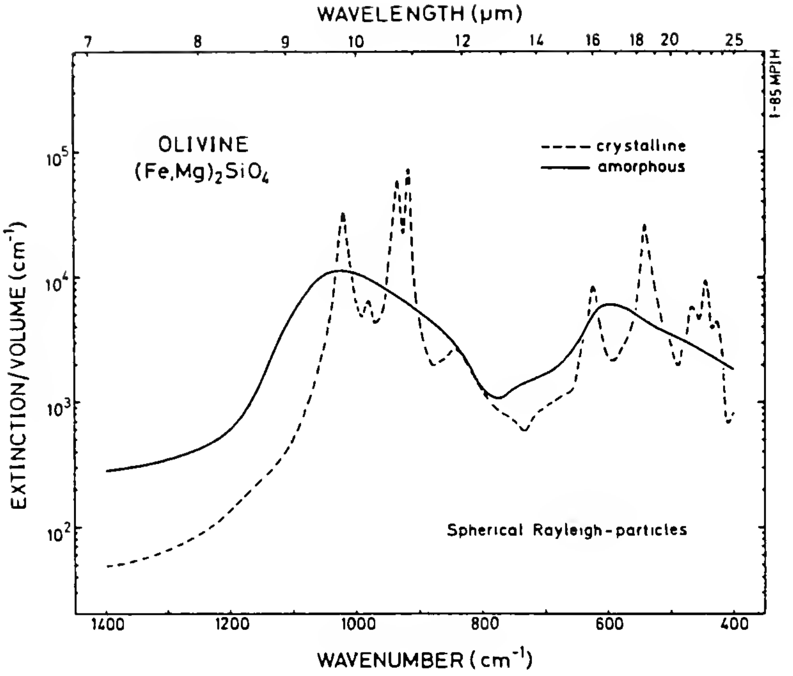

Fig.1: The extinction of the magnesium-iron-silicate called olivine in the crystalline and in the amorphous state. The Fe/Mg ratio of this particualar silicate is about 10% by atom. The amorphous silicate was produced by ion-sputtering of crystalline olivine (for details, see Krätschmer, 1980).

Since, in the case of a crystalline structure, the detailed positions and strengths of the sub-structures depend on the chemical composition of the silicate, one may argue that a suitable mixture of a variety of crystalline silicates with all their different extinction sub-structures superimposed could mimic the interstellar extinction as well. I regard this case as unlikely. The absence of wiggles in the shape of the 9.7 um feature, the wavelength positions of the extinction peaks, the comparatively weak strengths of the interstellar silicate absorptions, all this together can be much more coherently explained by silicates with amorphous structure.

The amorphous state of a solid usually is thermodynamically metastable, i.e. the solid tends to re-crystallise at a rate which strongly increases with increasing temperature. Thus the interstellar grains possess an internal memory of their thermal history to which an observer has access via IR-spectroscopy. The temperature regime at which recrystallisation takes place and in which the silicate grains may be used as temperature probes amounts to several 100 K. This seems to be quite high compared to

average interstellar conditions. The amorphous structure of the so far observed interstellar silicates in fact suggests that they never were appreciably heated. In this context it may be noted that interstellar H_2O ice in dense clouds seems to exist in an amorphous structure as well (see e.g. Kitta and Krätschmer, 1983). Phase transitions of this material, detectable by IR spectroscopy, occur at much lower temperatures (several 10 K). It thus may be useful to exploit the thermal memory of the amorphous interstellar grain materials in future IR-astronomical studies to investigate the thermal conditions within various interstellar environments.

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Are Aromatic Hydrocarbons the Carriers of the Diffuse Interstellar Bands in the Visible ?

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Large Polycyclic Aromatic Hydrocarbons (PAH) are the likely origin of the formerly called "Unidentified IR Emission Features". We show that these molecules or their ions are also attractive candidates for the carriers of the Diffuse Interstellar Bands in the Visible (DIBs) : 1) they have optically active transitions in the visible ; 2) they can survive the UV photons in the Diffuse Interstellar Medium ; 3) they are the most abundant among the detected molecular species after H_2 and CO. In particular, they are better candidates than the long carbon chains that had been proposed previously. A laboratory effort is undertaken to search for a spectroscopic support to this point.

Following our hypothesis, one can predict the absence of the DIBs in special astrophysical environments such as those where all the carbon is locked up in CO. There are some indications that this is the actual situation but further observations are suggested.

Abstract: GRAIN ALIGNMENT BY FERROMAGNETIC IMPURITIES

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The observed wavelength dependence of linear polarization, and its variation from region to region (Wilking, Lebofsky, and Riecke, A. J., 87, 695, 1982), can be explained by the following assumptions: (1) Interstellar grains resemble interplanetary grains, in that they are composed of collections of small particles coagulated together into elongated masses. (2) A fraction of the small particles are ferromagnetic. Presumably these are either metallic Fe or magnetite, Fe_3O_4. (3) If and only if a large grain contains one or more magnetic particles is the grain aligned in the galactic magnetic field. (4) The magnetic particles stick only to silicate grains because of chemical similarities, or (equivalently) any pure-carbon grains in the diffuse ISM are too spherical to produce polarization. (5) Grains in dense regions, such as the outer parts of molecular clouds, are larger than those in the diffuse ISM because of coagulation of the grains rather than accretion of icy mantles. These regions are known to have larger than normal values of $\lambda(max)$, the wavelength of the maximum of linear polarization.

The above assumptions are sufficient to allow the calculation of the wavelength dependence of the polarization, assuming that aligned particles behave like spinning cylinders. There is a free parameter, which is the size of the grain which has a probability of 0.5 of containing one or more magnetic particles. With the standard MRN power-law size distribution I recover the average $p(\lambda,\lambda(max))$ relationship ("Serkowski's Law"), which is a function containing two parameters. For dense regions, the size distribution of the coagulated particles determines the form of $p(\lambda,\lambda(max))$. I have tried two different but possible forms of the size distribution; both of them can provide the observed polarization. The correct size distribution for the coagulated particles depends on such quantities as the probability of shattering large particles by small ones, as opposed to sticking the two together. However, it is clear that coagulation of grains can lead to a size distribution which gives both the correct wavelength dependence of polarization and its variation from region to region.

SPECTRAL CHARACTERISTICS OF DUST IN PLANETARY NEBULAE

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ABSTRACT

Some carbon-rich planetary nebulae exhibit a strong broad emission feature beginning at $\lambda \sim 24\mu m$ and extending to $\lambda > 30\mu m$ (Forrest et al., 1981). We present 30-55μm spectrophotometry of IC 418 and NGC 6572, both of which have the strong broad emission feature. These observations allow us to define the wavelength dependence of the emissivity of the dust responsible for the feature.

Comparison with laboratory spectra of candidate materials which are likely to condense in a carbon-rich environment (Lattimer, Grossman, and Schramm, 1977), suggests that the feature arises from MgS (Goebel, 1980; Goebel and Moseley, 1984). Adopting this identification, we discuss the implications of such a strong feature arising from a relatively minor dust constituent.

Finally, we comment on the environment in which MgS may be found. We speculate that MgS will be seen in objects with C/O ratios only slightly greater than one, but not in extremely carbon-rich objects. In objects with much higher carbon abundances, e.g. BD+30°3639, the formation of CS consumes S so that insufficient MgS can form to exhibit the strong feature. These observations imply that the emergent far infrared spectrum of carbon-rich objects are very different depending on the abundance of the low temperature condensate MgS.

THE EFFECTS OF CHARGED DUST GRAINS ON IR MOLECULAR EXCITATION. R. Puetter and I. Krinsky, Center for Astrophysics and Space Sciences, UCSD. In this abstract we discuss a number of issues involving grain charging in the interstellar medium. Such effects include (1) Stark broadening of molecular spectral features, (2) electrostatic grain rupturing, (3) enhancements in particle-grain collision cross sections, and (4) excitation of molecular rotations and/or vibrations.

It has long been know that interstellar grains have an electric charge (see, for example, Spitzer's book "Physical Processes in the Interstellar Medium"). Simple arguments give electrostatic potentials of a few times kT of the gas. (Here we will be largely concerned with grains charged by sticking collisions with hot electrons; consequently the grains will be negatively charged. The effects of positive, photoelectrically charged grains, however, can also be important and should not be ignored.) Thus, for grains with a radius of $0.03\mu m$, the electric field, $\vec{\varepsilon}$, at the grain surface will be of the order 10^6 volts per centimeter or $3x10^3$ in cgs units. Note that smaller particles would acquire an even higher surface field, resulting in the onset of significant field emission. Furthermore particle breakup will occur under such high fields, especially if the tensile strength of the particles is low such as in lose particle agregates. At the smallest sizes (e.g. a few times 10^{-3} μm) only strong refractory grain cores are able to survive particle potentials of a few volts (Hill and Mendis 1979, The Moon and the Planets, 21, 53).

The Stark broadening of a rigid rotator in an electric field can be easily calculated, giving a fractional shift in the rotational energy, E, of $\Delta E/E \approx d\vec{\varepsilon}/E$ where d is the permanent dipole of the molecule. Since molecules typically have permanent dipoles of the order of a few debyes (1 debye $\equiv$ 10^{-18} esu cm, and we shall assume throughout that d=3 debyes), we find $\Delta E/E$ to be roughly 30. Hence under these conditions the Stark effect is much more than a small perturbation on the quantum mechanical states and causes any rotational sub-structure to be "washed out".

It should be noted that through Stark broadening the large electric field will affect both gas phase rotators and molecular rotators trapped in ice mantles. Furthermore, the strong electric field may also affect the quantum mechanics of surface states and solid state transitions.

The presence of charged grains also affects the collision cross sections for charged particles. Quite obviously, grains and particles of like charge are repelled, while grains and particles of opposite polarity are attracted. The enhancement to the collision cross section over the geometric cross section is well known (again see, for example, Spitzer's book "Physical Processes in the Interstellar Medium") and is given by Q =

$1 + (2eZV/3kT)$, where e is the charge on the electron, Z is the charge on the particle, V is the potential of the grain, and T is the kinetic temperature of the particle. For example, for positive molecular ions with a kinetic temperature of 100 K passing by a negatively charged grain of 3 volt potential, the enhancement to the geometric cross section is Q = 233.

We would also like to point out that charged grains may give rise to the well known unidentified infrared emission features seen at wavelengths of 3.3, 3.4, 3.5, 6.2, 7.7, 8.6, and 11.3μm in a wide range of astrophysical objects (including the spectrum of the galaxy M82--Willner et al. 1977, Ap.J.(Letters), 217, L121). These features apparently originate in the interface regions between the hot H II gas and the molecular cloud material (see Willner, Puetter, Russell, and Soifer 1979, Astrophys.SpaceSci., 65, 95, and references therein). Such a spatial correlation naturally suggests a molecular origin for the observed emission. This explanation is further strengthened by the fact that the 2 to 20μm spectral region is the "molecular signature" region in which most molecules emit strong rotation-vibration spectra. Based on the observation that the 3.3μm feature does not break up into the standard rotation-vibration structure under high spectral resolution (Grasdalen and Joyce 1976, Ap.J.(Letters), 205, L11 and Tokunaga and Young 1980, Ap.J.(Letters), 237, L93), most authors currently agree that if molecules are responsible for the observed emission, then they occur in the solid state as volatile mantles on more refractory grain cores. Two competing theories of the origin of this molecular emission are presently in favor: (1) thermal emission from grains containing volatile mantles (see Dwek, Sellgren, Soifer, and Werner 1980, Ap.J., 238, 140) and (2) UV fluoresence of molecules in volatile mantles (see Allamandola, Greenberg, and Norman 1979, Astron.Astrophys., 77, 66). Both of these senarios face problems. In the thermal emission case, an astronomical object has been found which apparently requires dust temperatures which are quite high ($T_{dust} \simeq 10^3$ K), considerably higher than expected and which remain constant independent of the distance to the exciting source (Sellgren, Werner, and Dinerstein 1983, Ap.J.(Letters), 271, L13). In the UV fuoresence senario, on the other hand, the effeciency of the conversion of UV photons into IR transitions must be very high, perhaps unacceptably high (Dwek, Sellgren, Soifer, and Werner 1980, Ap.J., 238, 140).

There might be several ways in which charged grains could give rise to the unidentified emission features. First, charged molecular ions might be attracted to charged grains, accelerated to several electron volt kinetic energies, and collide into the grain. Such collisions would certainly have sufficient energy to excite vibrational transitions, if not sufficient to break up the molecule. Furthermore, due to the Stark effect, such emission would not show the typical rotational sub-structure

since adjacent rotational states would be smeared together. A second senario would involve close passage of molecules and grains. Classical calculations of molecular proportioned, dipole rigid rotators demonstrate that the torques exerted on molecules during a grain passage can change the rotational energy of the molecule on the order of the dipole-electric field energy. Once the molecule is in such excited rotational states, it might be possible for rotation-vibration coupling to distribute the energy into vibrational motion.

Having proposed several mechanisms, we now turn to an analysis of the amount of observable emission that might result from these processes. The volume emissivity of both processes can be estimated from

$$4\pi j = h\nu\, N_{vib} v_{mole} n_{grain} \sigma$$

or

$$4\pi j = h\nu\, N_{vib} v_{mole} \sigma\, n_H^2\, (n_{mole}/n_H)(n_{grain}/n_H)$$

where N_{vib} is the number of vibrational transitions a molecule experiences in passing by or colliding with a grain, σ is the grain-molecule cross section ($\equiv \sigma_0$, the geometric cross section for neutral molecules; $\sigma_0 Q$ for charged molecular ions), and v_{mole} is the relative velocity of the molecule and grain. Assuming a gas to dust mass ratio of 100, we find

$$4\pi j = 2.8 \times 10^{-33}\, N_{vib} v_{mole} \sigma\, n_H^2\, Q (n_{mole}/n_H) \lambda^{-1} \quad ,$$

where λ is the wavelength in microns of the feature.

We can now estimate the flux of radiation received at the telescope. Assuming the emission fills an angular beam, Ω, of 10"x10", that we are looking through a path length, L, of material 0.2 parsecs long, that the value of Q is 300, that the hydrogen abundance is 10^6 (the density that might be expected in some of the denser condensations near the Orion molecular ridge), that the abundance of the revelant molecular species is 10^{-4} relative to hydrogen, and that v_{moles} is 2.6×10^4 cm s^{-1} (i.e. the velocity corresponding to a molecule of molecular weight 25 and a kinetic temperature of 100 K), the observed flux, F_{obs} ($\equiv jLQ\Omega$), received by the telescope is given by

$$F_{obs} = 2.4 \times 10^{-17} N_{vib} \lambda^{-1} \text{ W cm}^{-2}$$

Hence we see that the predicted brightness compares favorably with observed flux levels (a few times 10^{-17} W cm^{-2}, see, for example, the fluxes quoted in Dwek, Sellgren, Soifer, and Werner 1980). Slightly higher fluxes can be obtained by using smaller grains, although we must point out that this mechanism will only work with abundant molecular species in relatively dense regions. Still, small molecules and dust are known to exist in abundance in the gas phase in molecular cloud-H II region interfaces and shock processes in these regions will contribute to density enhancements. Thus, this interpretation of the unidentified emission features could be quite attractive.

WHAT PREDICTIONS CAN BE MADE ON THE NATURE OF CARBON AND CARBON-BEARING COMPOUNDS (HYDROCARBONS) IN THE INTERSTELLAR MEDIUM BASED ON STUDIES OF INTERPLANETARY DUST PARTICLES?

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The nature of hydrocarbons and properties of elemental carbon in circumstellar, interstellar and interplanetary dust has been a longstanding problem in astronomy and meteorite research. Sagan and Khare [1979] suggested that solid carbon-bearing molecules forming from simple gas mixtures are a major constituent in the interstellar medium, pre-planetary solar nebule, carbonaceous chondrites and comets. This solid material (tholins) forms a fluffy mixture of many carbon-bearing molecules, including carbon chain molecules [Winnewisser and Walmsley, 1979] and polycyclic aromatic hydrocarbons [Sagan and Khare, 1979; Leger and Puget, 1984]. Although the fit is not unique, the spectral characteristics of tholins fit many features in the IR spectra of circumstellar and interstellar dust. The 2175A extinction feature in the UV spectra of circumstellar and interstellar dust has been variously attributed to amorphous, poorly graphitised carbon (=turbostratic carbon) or graphite (=crystalline carbon) [Snow, this volume]. However, spectra for carbon-rich stars suggest the presence of amorphous carbon rather than graphite [Draine, 1984]. In an attempt to unify the observational data Greenberg [1982] proposed a three component dust model of tiny silicate and graphite grains and silicate grains mantled by "yellow stuff" of photo-processed molecules containing C, O, N and H. Greenberg [1982] showed that nonvolatile organic molecules of non-biotic origin are probably common to many comets.

Recently a new set of fine-grained extraterrestrial materials has become available to the scientific community through programs which collect these particles in the Earth's stratosphere [Fraundorf et al., 1982; Clanton et al., 1982]. These fine-grained materials are probably of cometary origin but may also originate in the asteroid belt, or in the interstellar medium [Brownlee et al., 1977]. An important subset of stratospheric dust collections is formed by fluffy aggregates of small-sized grains ranging from < 100A up to ~0.5um in size and which have chondritic bulk composition. The compositions of these Chondritic Porous Aggregates (CPA's) is comparable with the bulk compositions of carbonaceous chondrites [Fraundorf et al., 1982; Mackinnon et al., 1982] and matrices of unequilibrated ordinary chondrites [Rietmeijer and McKay 1985]. The extraterrestrial origin of CPA's is confirmed by their noble gas abundances [Rajan et al., 1977; Hudson et al., 1981] and large D/H fractionation ratios [Zinner et al., 1983; Wood, this volume].

In the past decade many detailed studies have shown that although CPA's have a varied silicate and oxide mineralogy, carbonaceous matter is invariably present [cf. McKay et al., 1985]. The mineralogy of some CPA's tentatively suggest a relationship between these aggregates and carbonaceous chondrites [Rietmeijer, 1985-a; Tomeoka and Buseck, 1985] or matrices of unequilibrated ordinary chondrites [Rietmeijer and McKay, 1985]. The measured D-excesses in many CPA's [Clayton, this volume; Wood, this volume] and inferred $^{12}C/^{13}C$ and $^{7}Li/^{6}Li$ ratios for cometary dust [Fechtig, 1981] suggest that CPA's (a subset of chondritic Interplanetary Dust Particles) may form a class of extraterrestrial materials that is even more primitive than primitive meteorites.

Hydrocarbons are indigenous to carbonaceous chondrites [Nagy, 1975] but the origin of individual molecules is uncertain. The isotopic signature of some

molecules (referred to as kerogen) suggests an origin in the interstellar medium [Kerridge, this volume]. Unfortunately we know little of the mineralogy of carbonaceous matter, including elemental carbon species, in primitive extraterrestrial materials. Analytical Electron Microscope (AEM) studies reveal that poorly graphitised carbon (PGC) is present in the Orgueil, Cold Bokkeveld and Allende meteorites [Lumpkin, 1981; 1983-a; -b; Smith and Buseck, 1981]. A few AEM studies of CPA's show that metastable carbon-2H [Rietmeijer and Mackinnon, 1985-a] and poorly graphitised carbon, similar to meteoritic PGC [Rietmeijer and Mackinnon, 1985-b], are the dominant carbon-bearing species, although "hydrocarbons" [Christoffersen and Buseck, 1984] may be present.

The mineral constituents of CI and CM carbonaceous chondrites indicate that these meteorites have been subjected to low-temperature ($T < 400^oK$) aqueous alterations [Bunch and Chang, 1980; Clayton and Mayeda, 1984]. The mineralogy of several CPA's shows that low-temperature aqueous, including hydrocryogenic, alterations, may have been operative in these aggregates [Rietmeijer, 1985-b; Rietmeijer and Mackinnon, 1984; 1985-c; Tomeoka and Buseck, 1985]. These observations raise the question to what extent hydrocarbon and elemental carbon phases are indigenous to primitive extraterrestrial materials or how much they have been affected by, or may have formed during, low-temperature alteration processes.

The textures and crystallographical properties of PGC from carbonaceous chondrites and CPA's are comparable with PGC formed by dehydrogenation and carbonisation of hydrocarbon precursors under natural terrestrial and experimental conditions [Rietmeijer and Mackinnon, 1985-b]. The degree of graphitisation of PGC shows a systematic relationship with the heat-treatment temperature or duration of peak-heating. The minimum graphitisation temperature for PGC in the CPA's and carbonaceous chondrites is ca 400^oK [Rietmeijer and Mackinnon, 1985-b]. Importantly, in CPA's, but not in carbonaceous chondrites, PGC contains traces of another carbon phase identified as carbon-2H [Rietmeijer and Mackinnon, 1985-a]. Carbon-2H is a metastable product of low-temperature hydrous pyrolysis of a hydrocarbon precursor and itself is a precursor of PGC [Rietmeijer and Mackinnon, 1985-a].

By analogy with terrestrial hydrocarbon and PGC occurrences Rietmeijer and Mackinnon [1985-d] proposed a multi-stage model of hydrocarbon diagenesis in CPA and carbonaceous chondrite (proto-) planetary parent bodies [Rietmeijer, 1985-a; -c] in which hydrocarbons are subjected to low-temperature hydrous pyrolysis. With continued heat-treatment time and temperature the pyrolysis products, e.g. carbon-2H, are graphitised to various degrees of PGC. Hydrous pyrolysis and graphitisation are sensitive to the presence of a catalyst, e.g. certain non-metallic elements, metals, alloys and layer silicates, which contribute to lower the temperatures at which these processes occur [Bradley et al., 1984; Fitzer et al., 1971; Mackinnon et al., 1985; Rietmeijer and Mackinnon, 1985-a; -b; Oya and Marsh, 1982].

In summary, elemental carbon phases in primitive extraterrestrial materials form *in situ* by low-temperature processes after accumulation of dust into (proto-) planetary parent bodies. Hydrous pyrolysis not only produces soft, well-graphitisable, carbon but may also result in the formation of new hydrocarbon molecules either from heavier hydrocarbon precursors or by reaction between pyrolysis intermediates [Fitzer et al., 1971]. In addition, hydrous pyrolysis may change the deuterium content of hydrocarbons [Hoering, 1982]. Thus, it seems not possible to recognise *a priori* an unprocessed hydrocarbon

phase in carbonaceous chondrites and CPA's.

Although hydrocarbons in primitive extraterrestrial materials present a complex model, I conclude that hydrocarbons, and not PGC or graphite, dominate the dust around carbon-rich stars and in the interstellar medium. This conclusion, based on observational evidence, supports experimental studies by Dayhoff et al. [1964] and Hayatsu et al. [1980] that vapor phase condensation in carbon-rich environments will produce hydrocarbons rather than graphite because of its high nucleation energy [Czyzak and Santiago, 1973]. We may probably rule out the existence of graphite, and possibly of PGC, in the interstellar medium if chemical processing in the interstellar medium occurs at energie levels comparable with simulation studies [cf. Greenberg, 1982; Sagan and Khare, 1979]. Additional energy sources may be the amorphous to crystalline transitions of silicates [Clayton, 1983] and ices [Smoluchowski and McWilliam, 1984].

In addition, hydrocarbons in primitive extraterrestrial materials may not be pristine interstellar molecules. However, continued efforts to recognise hydrocarbons and elemental carbon phases in Chondritic Porous Aggregates may allow us to understand the multi-stage hydrocarbon/elemental carbon model.

I like to thank Dr Ian Mackinnon for his generous cooperation and Dr Dave McKay for his support.

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WHY DO INTERSTELLAR GRAINS EXIST?

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There exists a discrepancy between calculated destruction rates of grains in the interstellar medium and postulated sources of new grains. We have examined this problem by modelling the global life cycle of grains in the galaxy. The model includes: grain destruction due to supernovae shock waves; grain injection from cool stars, planetary nebulae, star formation, novae, and supernovae; grain growth by accretion in dark clouds; and a mixing scheme between phases of the interstellar medium.

The principal results of calculations of the shock destruction of grains are that large grains (0.1 μm) are readily destroyed by thermal sputtering in very fast (200 - 400 kms^{-1}) non-adiabatic shocks. These destruction processes are insensitive to the nature of the grains involved. In particular, grain cores cannot be protected by any kind of mantling. Time scales for this destruction, averaged over the incidence of shocks in the various phases of the ISM, are on the order of 10^7 - 10^8 years. These rates are an order of magnitude smaller than the injection rates for fresh grains from various stellar sources. It is, therefore, difficult to account for the abundance of refractory grains in the ISM within this scheme.

The solution to this dilemma is to either increase the grain formation rate and/or to decrease the shock destruction rate. We are considering grain growth in molecular clouds as a mechanism for increasing the formation rate. To decrease the shock destruction rate, we are including several new physical processes, such as partial vaporization effects in grain-grain collisions, breakdown of the small Larmor radius approximation for betatron acceleration, and relaxation of the steady-state shock assumption.

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Chromospheric Dust Formation, Stellar Masers and Mass Loss

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ABSTRACT

I outline a multi-step scenario which describes a plausible mass loss mechanism associated with red giant and related stars. The process involves triggering a condensation instability in an extended chromosphere, leading to the formation of cool, dense clouds which are conducive to the formation of molecules and dust grains. Once formed, the dust can be driven away from the star by radiation pressure. Consistency with various observed phenomena is discussed.

New View of Red Giant Chromospheres

The analysis of cool stars has benefited from reference to the Sun as a well studied archetype. However, in the past few years, it has been recognized that the solar analogy must be applied with caution, especially in the case of much lower surface gravity. Quantitative analyses of red giant chromospheres use ultraviolet lines of singly ionized carbon, to derive temperature (Brown and Carpenter 1984), densities and physical extent (Carpenter, Brown and Stencel 1985; cf. Hartmann and Avrett 1984).

These analyses combined with other multispectral studies indicate that red giants and supergiants altogether lack solar-like coronae, but instead fill comparable volumes with extended warm gas having densities of order 10E7-10E8/cm3 at temperatures of order 8,000 degrees Kelvin. Chromospheric radial dimensions are at least several stellar radii; approximately 10E14 cm for the supergiants. Maintenance of this extended warm region can be accomplished by absorption ionization of UV and EUV photons. In what follows, I argue that cooling can occur in two co-existing thermal regimes: chromospheric UV line emission in "warm" regions, and via molecular masers and thermal emission from dust in "cool" regions. This thermal bistability may contribute to the observed mass loss and other properties of such stars (cf. Goldberg, 1983).

Cooling via Condensation Instability

Key point: if you compress a chromospheric gas (8000K, 1E7/cm3), a condensation instability occurs because as the density rises, the radiative cooling increases with the density squared. Because this happens on the very steep portion of the radiative power loss curve (cooling rate, ergs/cm3/sec-vs-temperature, cf. Raymond et al. 1976), there is a dethermalizing runaway to very low temperatures.

An original application of this physics was described by Field et al. (1969) for the two-phase interstellar medium, where they derived "two thermally stable gas phases that coexist in pressure equilibrium, one at 10,000K and the other cooler than 300K." Their model was derived for interstellar gas heated by low energy cosmic rays. The resulting partition cooled 75% of the gas.

Lepp et al. (1984) have more recently confirmed this basic result for matter in the presence of radiation fields. By including high energy photons, they also derived an inverse Compton term and thus a coronal gas phase. Although a steady state solution, this model replicates the three-phase interstellar medium and makes predictions for quasar clouds. The coronal result does not apply to stellar chromospheres which lack a source of hard photons. The range of pressures and heating/cooling channels described by Lepp et al. imply applicability to the lower temperature physics of the putative two-phase chromospheres.

Instability Trigger Mechanisms

Basic stellar structure suggests that red giants possess large convective envelopes in response to steep temperature gradients Schwarzschild (1975). Convective motion provides a source of "acoustic noise" that will give rise to pressure perturbations in an overlying atmosphere. The density enhancement can trigger the condensation instability. To avoid shock waves which could produce high temperature emission lines, either the input energy varies slowly or the density profile with height is less steep than exponential. I prefer the latter, anticipating a quasi-isobaric extended chromosphere. Many cool, evolved stars pulsate. Shock phenomena may dominate those atmospheres, but it is possible that this scenario plays a role in regions where, or at times when, shocks are less important.

Formation of Molecules and Dust

The condensation instability yields conditions appropriate for the formation of molecules and grains. As a result of the rapid cooling and enhanced densities, molecules are formed in excited states and then cool via maser emission. Recent work by Elitzur and Cooke (1985) states that H_2O masers occur for densities at and above 1E9,cm3, are collisionally pumped and correspond to a 1000K excitation temperature. This is exactly the higher density, lower temperature condition expected from the condensation instability. VLBI studies show SiO masers occuring within a few stellar radii of dusty objects, like IRC+10216 (Lane, 1982; Johnston, et al. 1985). While the detailed chemistry is still to be elaborated (Kozasa et al. 1984; Maciel 1973, 1976), we may be seeing a manifestation of the condensation instability process.

Interferometric mapping of the 10 micron emission associated with silicate dust grains indicates a lack of such emission inside of approximately 10 stellar radii in many dusty objects (cf. Sutton et al. 1977). However, molecular clusters and less-annealed silicates with spectral features at other than 10 microns could be forming within this inner dust radius. SiO masers within 10 stellar radii are probably associated with this chemistry. Chromospheric and

envelope expansion velocities require months - years for material to move several stellar radii. This places temporal constraints on cluster formation and subsequent dust nucleation (Donn and Nuth 1985). High spatial resolution observations of radial and azimuthal spectral variations may reveal the entire process.

Quenching Chromospheric Radiation/Accelerating Dust

Extended stellar chromospheres are optically thick to the usual radiative loss channels (hydrogen lines, Ca +, Mg +). The chromospheric gas is filled with photons of the Lyman series, scattered endlessly and effectively trapped (Wilson 1960). This radiation field could act on the newly condensed molecules and grains to provide acceleration and eventual expulsion. Jura (1984; 1985) has already concluded that once grains form near these stars, radiation pressure can accelerate them to infinity.

An extended chromosphere could trap part of the star's bolometric luminosity in endlessly scattered Lyman transitions. A 10E-7 Mo/yr mass loss at 10 km/sec requires an energy content which is comparable to less than 10E-4 of the bolometric luminosity. If we "quench" these chromospheric photons, transferring their energy to mass motion of grains, the net effect will be a lack of, or reduction of observed ultraviolet chromospheric emission, as discovered by Hagen, Carpenter and Stencel (1985). The radiative transfer applicable to this reduction of resonance line flux was discussed by Wehrse and Kalkofen (1985), where factors of five in flux reduction were derived. In light of the detection of UV chromospheric emission from dusty stars, this scenario provides an alternative to the quenched chromosphere idea of Jennings and Dyck (1972), which was based on the lack of Ca II emission in dusty stars.

Further Work

To further investigate the validity of this scenario, several lines of work are required. First, the timescale for the growth of the instability needs to be evaluated, against the constraint of the "fully formed" 10 micron silicate dust emission features outside of ten stellar radii. Second, an observational test involving high spatial resolution spectral imaging is needed to monitor radial and azimuthal changes in the infrared dust emission profiles, in response to nucleation, growth and processing of dust grains in the circumstellar environment. Finally, the role of this process in the atmospheres of cool, pulsating stars deserves study. I am happy to acknowledge useful discussions with Joseph Nuth and Leo Goldberg in the preparation of this report.

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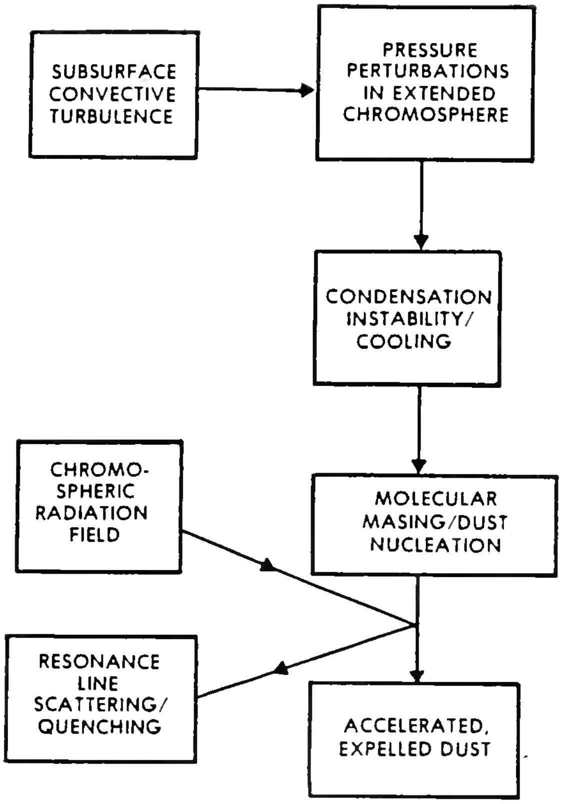
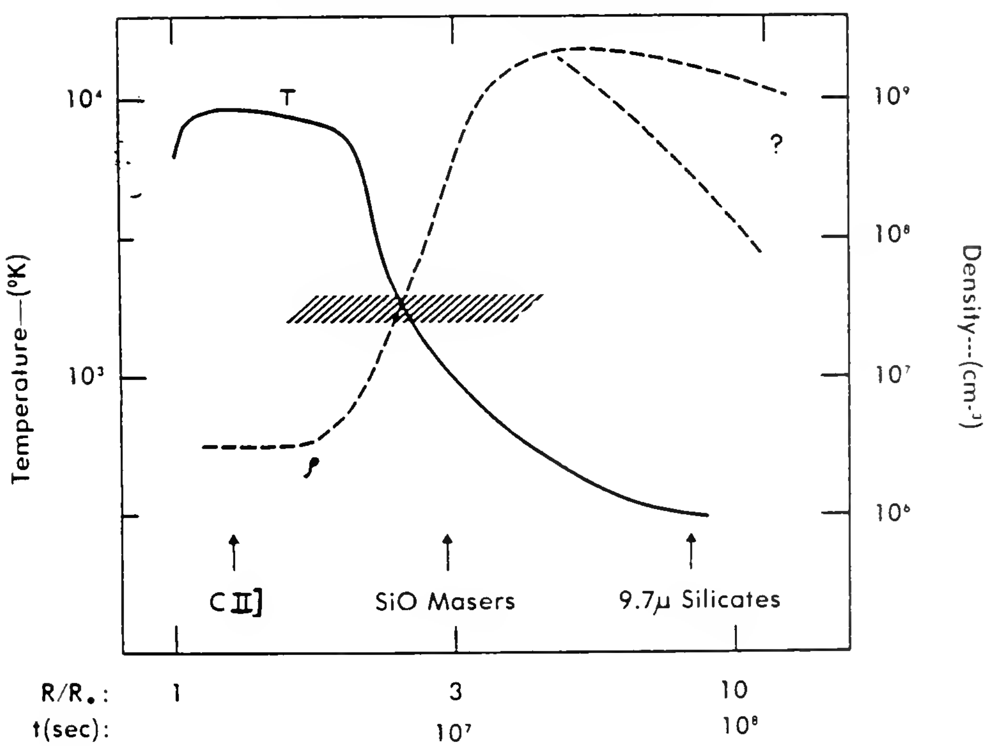


Mass Loss Scenario

CSE Thermal Instability



PREPARATION, ANALYSIS, AND RELEASE OF SIMULATED INTERPLANETARY GRAINS INTO LOW EARTH ORBIT

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LAUR-85-1979

I. INTRODUCTION

Astronomical observations which reflect the optical and dynamical properties of interstellar and interplanetary grains are the primary means of identifying the shape, size, and the chemistry of extraterrestrial grain materials and is a major subject of this workshop. Except for recent samplings of extraterrestrial particles in near-Earth orbit and in the stratosphere (see R. L. Walker, this volume) observations have been the only method of deducing the properties of extraterrestrial particles. In order to elucidate the detailed characteristics of observed dust, the observations must be compared with theoretical studies, some of which are discussed in this volume, or compared with terrestrial laboratory experiments.

Such experiments typically seek not to reproduce astrophysical conditions but to illuminate fundamental dust processes and properties which must be extrapolated to interesting astrophysical conditions. In this report, we discuss the formation and optical characterization of simulated interstellar and interplanetary dust with particular emphasis on studying the properties on irregularly shaped particles. We also discuss efforts to develop the techniques to allow dust experiments to be carried out in low-Earth orbit, thus extending the conditions under which dust experiments may be performed. The objectives of this study are three fold:

1. Elucidate the optical properties, including scattering and absorption, of simulated interstellar grains including SiC, silicates, and carbon grains produced in the laboratory.

2. Develop the capabilities to release grains and volatile materials into the near-Earth environment and study their dynamics and optical properties.

3. Study the interaction of released materials with the near-Earth environment to elucidate grain behavior in astrophysical environments. Interaction of grains with their enviroment may, for example, lead to grain alignment or coagulation, which results in observable phenomena such as polarization of light or a change of the scattering properties of the grains.

II. EXPERIMENT AND DISCUSSION

1. Grain preparation and physical characterization

The grains may be prepared by injecting a gas mixture, including volatile precursors containing the elements of interest, into an inductively coupled plasma system. The volatile precursors, mixed with other reactant gases, for

example hydrogen, argon, and N_2O are pyrolized in the high temperature plasma to an elemental gas. The grains are formed by condensation from the gas in the relatively low temperature tailflame of the plasma. For example, SiC or silicate grains may be prepared by mixing combinations of CH_4, $Fe(CO)_5$, and SiH_4 into the plasma feed gases. A schematic of such a plasma system, currently used by Los Alamos researchers to form refractory ceramics is shown in Figure 1 (from Vogt et al., 1984). Nearly any gas mixture can potentially be prepared by using a combination of gaseous, liquid, and powder feed materials. The system shown operates at near atmospheric pressure, and local thermodynamic equilibrium is believed to be maintained throughout the condensation process. Powders can be prepared in the kilogram quantities necessary for release experiments into orbit.

The particles produced occur as tangled strings of submicron grains typical of laboratory produced grains. Figure 2 shows silicate, SiC, and carbon grains prepared by another method, vaporizing a solid into a rarified gas using a laser (Stephens, 1980). The diffraction patterns for the "olivine" silicate, SiC, and carbon grains indicate that the grains are amorphous, highly crystalline B-SiC, and glassy, respectively.

2. Optical characterization of grains

Although the individual grains produced in the plasma are too small to produce significant scattering of visible and infrared radiation, the agglomerated grains have shown measurable scattering to wavelengths at least 10 microns in the infrared (Stephens and Russell, 1979). Such elongated grains could also cause polarization of starlight if they are aligned. A laboratory apparatus is being constructed to study the absorption, scattering, and light polarization properites of these highly irregular particles as a function of scattering angle and wavelength. A schematic of the laboratory apparatus is shown in Figure 3. The apparatus consists of a solar simulator light source with optional monochromator and polarizer which illuminates a scattering chamber of several liters volume in which particles are suspended in a gas. Scattering from the particles is detected by a combination monochromator-optical multichannel analyzer (OMA) which is sensitive over the wavelength range of 300 to 900 nm. The apparatus measures the wavelength and polarization resolved scattering of particles averaged over particle shape and orientation and is complementary to instruments which measure single particle scattering at a single wavelength. Planned enhancements to the system include adding a quartz element mass monitor to measure aerosol mass and a photoacoustic detector to allow measurement of aerosol absorption.

In conjunction with the optical measurements of laboratory-produced particles, microwave analogue studies, in collaboration with the Space Astronomy Laboratory at the University of Florida at Gainesville and the Ruhr University at Bochum, Germany are planned. The microwave analogue technique uses microwave radiation scattered from cm sized "grains" with the appropriate complex index of refraction to simulate scattering of visible radiation from micron-sized particles. The technique allows accurate measurements of irregular particle scattering to be made which are not possible by direct measurements on real particles. The microwave analogue measurements on scaled single particles complement our measurements on a cloud of particles.

3. Grain packaging, release, and monitoring of grains in low-Earth orbit

The thrust of the orbital release experiments is to monitor the dynamics and optical signatures of well characterized laboratory grains released into near-Earth orbit to elucidate the behavior of grains in astrophysical environments. Several kilograms of laboratory-prepared dust will be required for dust release experiments in orbit. Initially, refractory dusts including silicates, SiC, or carbon are planned for release. Later, releases of mixtures of dust and volatile materials, to simulate a comet nucleus, are possible. It is presently planned to collect the dust immediately upon preparation by the plasma system in a liquid or solid binder to inhibit grain coagulation during storage. A high vapor pressure liquid or subliming binder are being considered. Samples of the grains prepared will be characterized physically and optically, as outlined above, to provide baseline data for the observations of the grains in orbit.

Grain releases will be carried out from the Space Shuttle Orbiter using a Get-Away-Special cannister with the capability of releasing a small satellite (XSAT), which is approximately 45 cm on a side, with a weight capacity of 150 pounds. The XSAT, containing the grains, binder, and supporting electronics is ejected from the Shuttle by a crewmember while in orbit. After the shuttle has deorbited, activity on the XSAT may be initiated by radio. Aerosols are released from the binder using resistive heating or exothermic chemical reaction. The Get-Away Special cannister containing the ejection mechanism has been tested on a recent shuttle flight. The XSAT deployed in the recent shuttle flight was developed by the experimenters. NASA has proposed to develop a generic XSAT with telemetry, limited attitude control, and programmable data controller capabilities. The lifetime in orbit would be up to a year with solar cells. A photograph of the get-away-special ejector is shown in figure 4 in cutaway view with the top open.

Initiation of the grain release from the XSAT and observations will be carried out from the AMOS/MOTIF observatory on Mt. Haleakala on Maui in the Hawaiian Islands. Grain release will be initiated at a time such that the grains pass overhead near the terminator, with the grains illuminated by the sun, but the ground in darkness. Observations will be performed as the grains pass overhead, yielding scattering data as a function of sun-grain-observer scattering angle. Possible observations include total scattered intensity, cloud imaging, and also visible and infrared spectrometry. Polarization resolved observations of scattered light, which may result from grain streaming or alignment by the Earth's magnetic field, will be carried out if the signal is sufficiently strong. Fundamental questions to be answered include the magnitude of the atmospheric drag on the particles, efficiency of grain alignment caused by streaming through the atmosphere or alignment with the Earth's magnetic field, and charging of the particles which can have a major effect on their orbital trajectory.

III. CONCLUSIONS

The above program is aimed at elucidating the scattering properties of irregular, coagulated dust composed of candidate materials for interstellar and interplanetary dust. In addition, this program attempts to extend the physical conditions under which dust may be studied by extending laboratory

studies to the near-Earth environment. We have outlined several phenomenon of fundamental interest to the study of interstellar and interplanetary dust which will be investigated. The orbital release studies outlined above represent only a beginning of what is possible. Releasing mixtures of refractory grains and volatiles to simulate comet processes near perihelion is one potentially fruitful avenue of research. Simulated comet releases could be used not only to study cometary processes, but also to test instruments designed for comet rendezvous missions. Such studies would take advantage of the Shuttle as an observation platform for performing space experiments. Suggestions and collaborations involving observations, experiments, and equipment design are welcome.

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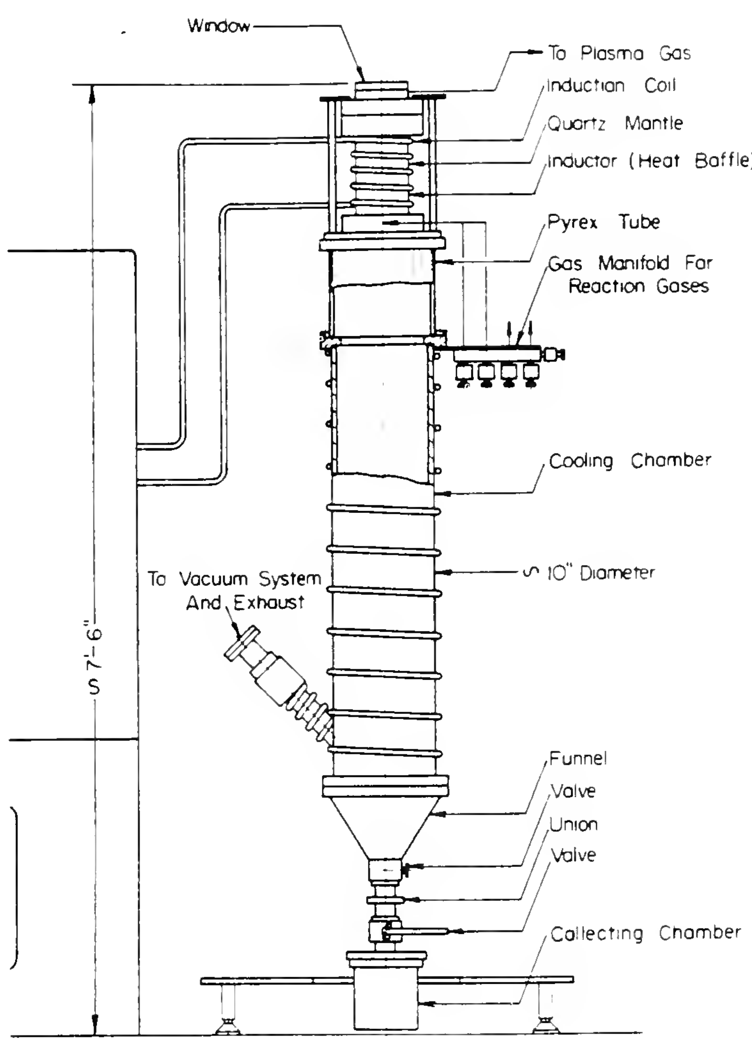

Figure 1

Schematic of plasma system used to generate grain materials. The reaction gases are injected below the plasma induction coil. Grains form in the cooling chamber and are collected in the collection chamber.

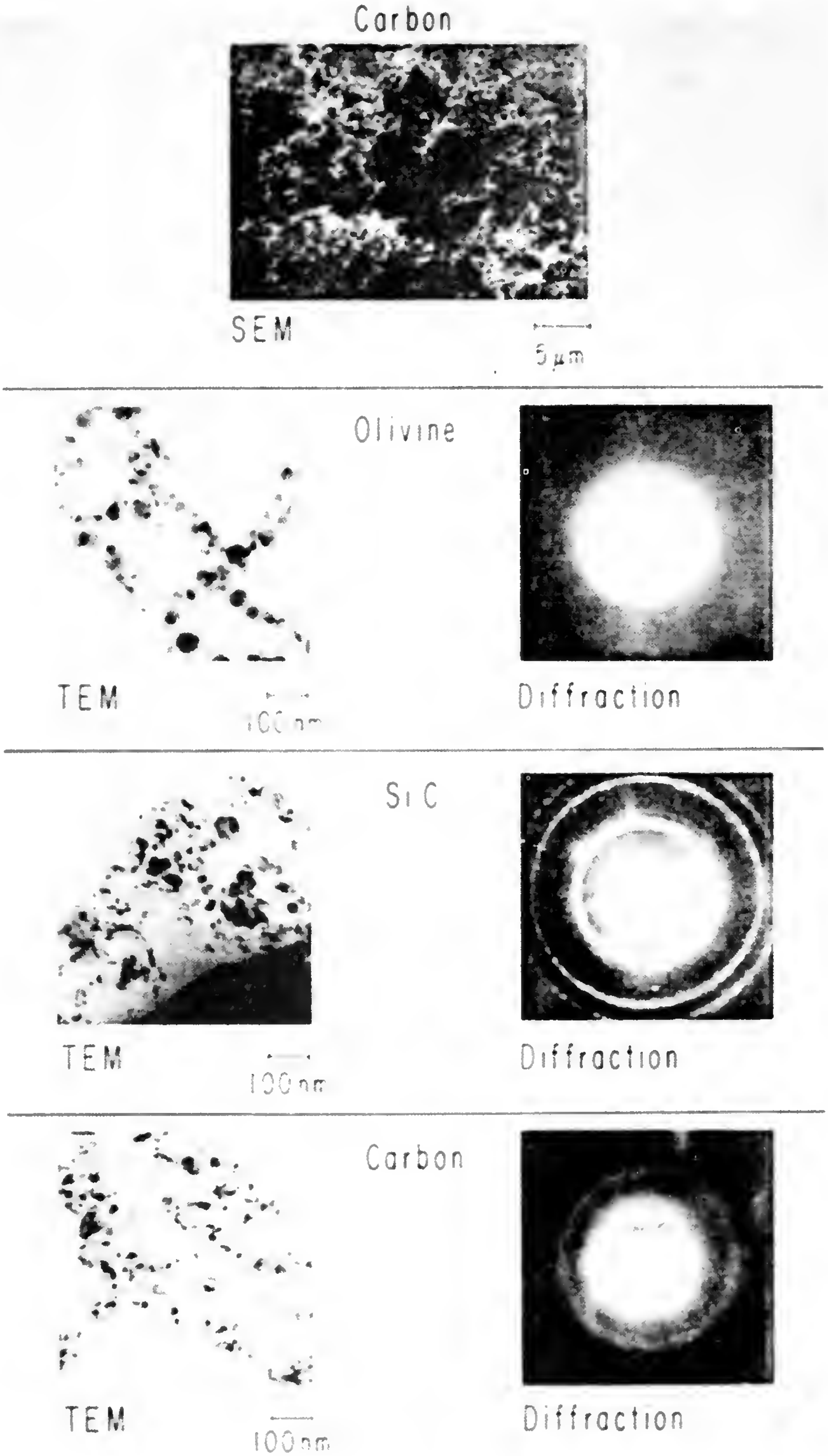

Figure 2
Scanning (SEM) and transmission (TEM) electronmicrographs and electron diffraction patterns of an amorphous silicate (olivine), SiC, and carbon condensate grains. The silicate, SiC, and carbon grains are amorphous, crystalline β-SiC, and glassy, respectively.

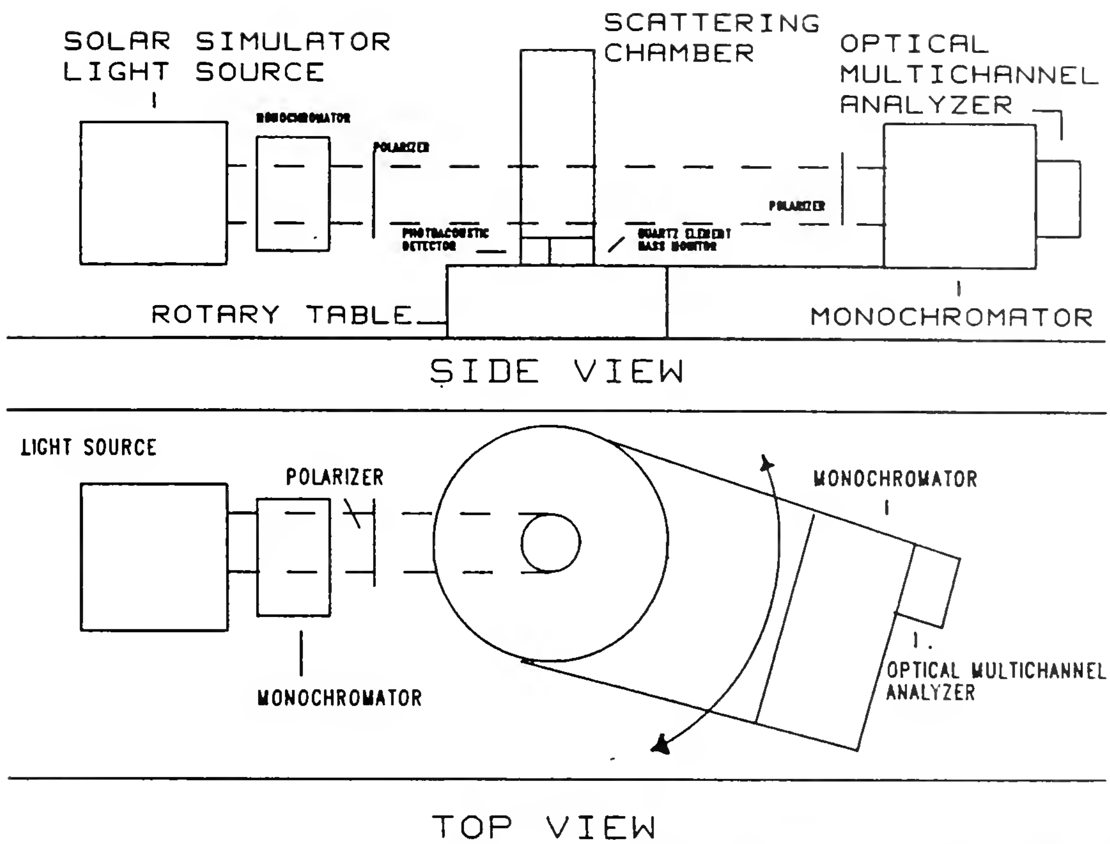

Figure 3
Schematic of laboratory apparatus for measuring light scattering from grains as a function of wavelength and angle. For details see text.

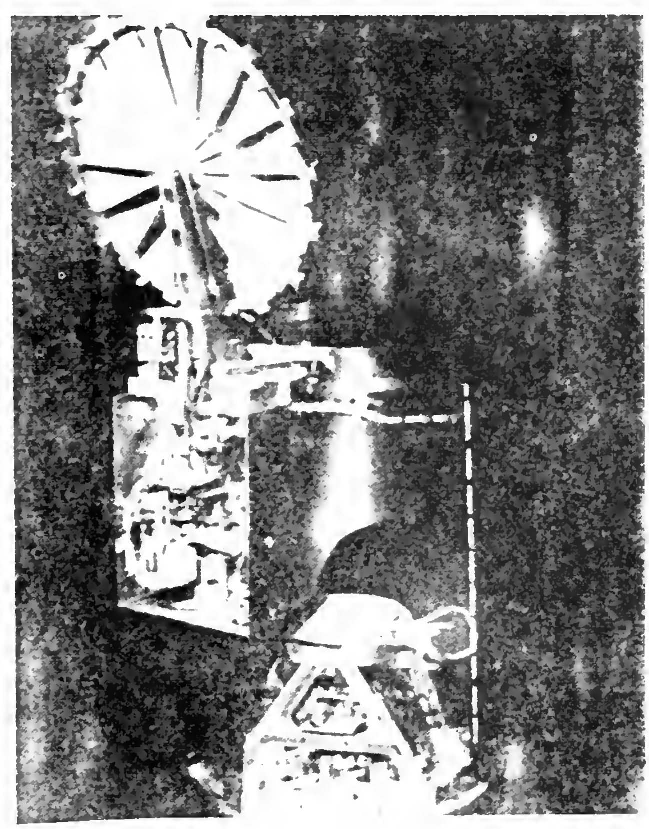

Figure 4
Photograph of Get-Away-Special ejector for launching a small satellite from the Space Shuttle Orbiter. The ejector is shown in cutaway with the top open.

Interstellar Grain Mantles

A.G.G.M. Tielens, L.J. Allamandola, J. Bregman and F.C. Witteborn

NASA/Ames Research Center
Moffett Field, CA

Interstellar molecular ("icy") grain mantles are an important component of the interstellar dust inside dense molecular clouds as evidenced by the detection of absorption bands at 2.97, 3.08, 4.61, 6.0 and 6.8 microns. They may also be the precursors of more-complex grain mantles in the diffuse interstellar medium.

We have calculated the molecular composition of these "icy" grain mantles employing gas phase as well as grain surface reactions. The calculated mixtures consist mainly of the molecules H_2O, H_2CO, N_2, CO, O_2, H_2O_2, NH_2, and their deuterated counterparts in varying ratios. The exact compositions depend strongly on the physical conditions in the gas phase. The absorption spectra of H_2O with other molecules have been studied in the laboratory. Optical constants have been determined for a few selected mixtures. Extinction and polarization cross sections across the 3um ice band have been calculated. A comparison with the observations towards BN shows that the low frequency wing observed on this feature is due to absorption by a mixture of H_2O and other molecules rather than scattering by large, pure H_2O ice grains.

Recently, high signal to noise (5-8um) spectra have been obtained of several component sources embedded in dense molecular clouds. The observed absorption features at 6.0 and 6.8um show variation from source to source. The 6.0um feature is attributed to the OH bending mode in H_2O, in line with the identification of the 3.08um band as the OH stretch in H_2O. A varying contribution of the C=O stretch in ketones, aldehydes, esters or carboxylic acids may be responsible for the observed variations in this band. The 6.8um band is due to the CH deformation mode probably in alcohols. The variations observed in this band are probably due to the presence of unsaturated hydrocarbons or saturated hydrocarbons with strongly electro negative groups in some of the sources as well. The observed variations imply a very rich chemistry, suggesting that energetic processing of grain mantles, such as UV photolysis, may be important.

EXCIMER EMISSION OF POLYAROMATIC HYDROCARBONS AS THE MECHANISM OF BROAD-BAND VISIBLE FLUORESCENCE OF INTERSTELLAR DUST,

Thomas J. Wdowiak, Department of Physics, University of Alabama at Birmingham, Birmingham, AL, 35294

Introduction. Considerable interest exists in polyaromatic hydrocarbons (PAH's) as an interstellar constituent (Leger and Puget 1984, Puget et al. 1985, Leger and d'Hendecourt 1985, Allamandola et al. 1985a, Allamandola et al. 1985b, and Van der Zwet and Allamandola 1985) responsible for infrared emission bands, far infrared "cirrus" emission, and the diffuse interstellar bands at visible wavelengths. These recent discussions are founded on earlier examinations by Platt (1956, 1960) and Donn (1968). It is the purpose of this discussion to demonstrate observed fluorescence of dust grains (Schmidt et al. 1980, Warren-Smith et al. 1981, and Witt and Schild 1985) might be explained by PAH excited dimer emission, although other molecúlar species could be responsible (Wdowiak et al. 1985).

Excimer Emission. The spectrum of the Red Rectangle (HD44179) exhibits a broad emission feature from 5500A to 7500A (Fig.1) (Schmidt et al. 1980). This broad feature is punctuated with narrower emissions of molecular origin. The character of the spectrum is not unlike that of the PAH pyrene at 10-2 Molar concentrations in solvents such as ethanol and in the crystalline form (Fig.2) (Stevens 1962) except that pyrene emission is at shorter wavelengths (<5500A).

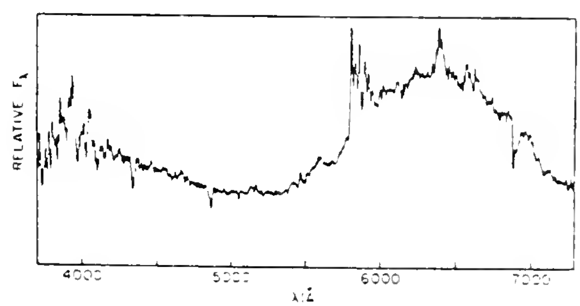

Fig.1 The spectrum of the Red Rectangle.

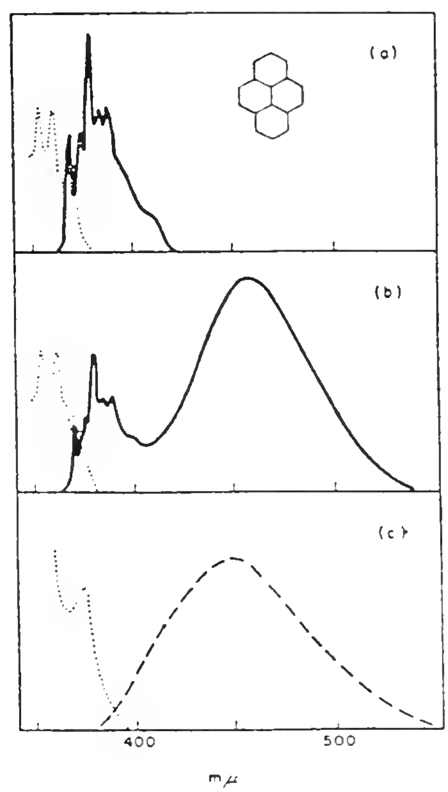

Fig.2 Absorption (. . . .) and fluorescence (——) spectra of pyrene; (a) 10^{-4} M in ethanol; (b) 10^{-2} M in ethanol; (c) absorption [22] (. . . .) and emission (– – –) spectra of crystalline pyrene.

At low concentrations where molecules have no near neighbor, the molecule exhibits monomer fluorescence at shorter wavelengths (Fig.2a). With increasing concentration (Fig.2b) and in the crystalline state (Fig.2c), a shift in the spectrum from shorter wavelength structured emission to longer wavelength unstructured emission occurs. The shift is explained by the formation of excited dimers from excited singlet molecules (A*) and unexcited ones (A)

$$A^* + A \longrightarrow A^*A$$

followed by a radiative transition

$$A^*A \longrightarrow AA + h\nu$$

and rapid dissociation into monomers.

$$AA \longrightarrow A + A$$

While the 4-ring PAH pyrene has excimer emission peaked at 4800A, 6-ringed anthanthrene peaks at 6000A for a 10^{-2} molar solution in benzene (Fig.3) (Birks and Christophorou 1964) and at 6400A as microcrystals (Fig.4) (Northrop and Simpson 1956). The difference can be explained by the larger electron box of the 6-ring molecule.

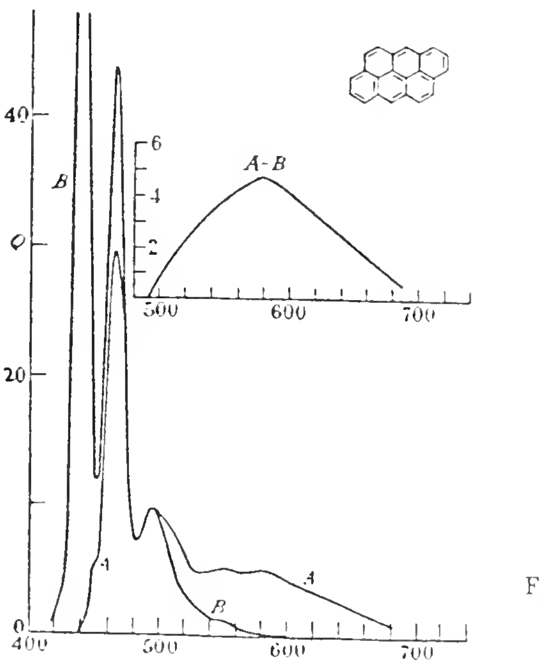

Fig.3 Anthanthrene in benzene. A, 10^{-2} M; B, 10^{-4} M.

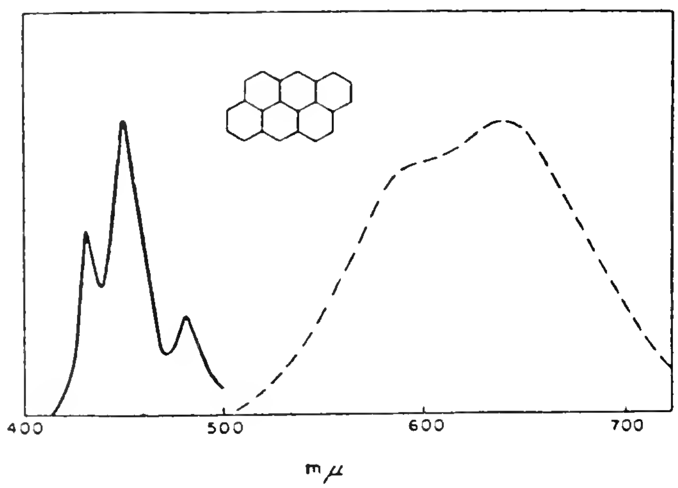

Fig.4 The fluorescence spectra of anthanthrene in solution (——) and as microcrystals (– – –)

Discussion. The suggestion of PAH's as an interstellar constituent and the excimer emission process is attractive for explaining observed broad band emission such as that of the Red Rectangle and the reflection nebula, NGC 2023, in terms of large PAH's existing on the surfaces or in the interiors of grain mantles. It should be pointed out that the excited dimer can be composed of different molecules as demonstrated by mixed dimer emission from pyrene crystals containing perylene (Hochstrasser 1962). The result is richness in possible combinations because it is unrealistic to consider interstellar PAH's to be a few specific molecules. For example coal tar prepared from coking coal contains over 400 identified polyaromatic species.

Excimer emission of PAH's increases with decreasing temperature because the excited dimer is relatively long-lived and disassociation prior to the radiative transition occurs more frequently at higher temperatures. Thus the process is expected to be more efficient at low interstellar temperatures.

If PAH's are responsible for the far IR "cirrus," they may exhibit visible emission. Perhaps this emission may be a component of the diffuse galactic light at red wavelengths.

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ULTRAVIOLET SPECTROSCOPY OF METEORIC DEBRIS OF COMETS, Thomas J. Wdowiak, Department of Physics, University of Alabama at Birmingham, Birmingham, AL, 35294, William R. Kubinec, Department of Physics, College of Charleston, Charleston, SC 28424, and Joseph A Nuth, Solar System Exploration Div., NASA HQ, Washington, DC 20546

Introduction. It is proposed to carry out slitless spectroscopy at ultraviolet wavelengths from orbit of meteoric debris associated with comets. The Eta Aquarid and Orionid/Halley and the Perseid/1962 862 Swift-Tuttle showers would be principal targets. Low light level, ultraviolet video technique will be used during night side of the orbit in a wide field, earthward viewing mode. Data will be stored in compact video cassette recorders. The experiment may be configured as a GAS package or in the HITCHHIKER mode. The latter would allow flexible pointing capability beyond that offered by shuttle orientation of the GAS package, and doubling of the data record. The 1100-3200 A spectral region should show emissions of atomic, ionic, and molecular species of interest on cometary and solar system studies.

Discussion. Analysis of middle to far ultraviolet spectral data of meteoric debris of cometary origin has yet to be carried out. Objectives of such a study include:

1. Observation of many of the atomic species, both neutral and ionized, including the strong feature due to MgI at 2850A and the strong blend at 2800A due to MgII and MnI. An interesting possible metal emission is that of BeI at 2349A.

2. Carbon is an expected constituent of comet-associated meteors. Though spectral features can exist in the visible region, carbon cannot be observed due to masking, principally by iron. The 1000-2000A region should be relatively free of FeI and FeII emission allowing observation of CI 1193A, CI 1330A, CI 1561, and CI 1657A. In addition, strong SiI and SiII emissions exist in the region suggesting determination of the C/Si ratio.

3. Lyman alpha emission at 1215A due to hydrogen from H_2O and hydrocarbons. The video technique allows examination of temporal development of expected strong Lyman alpha.

4. Sulfur at 1807A, 1820A, and phosphorus at 1672A, 1675A, 1680A, and 1775A. Sulfur is a relatively abundant component of carbonaceous chondrites and its existence in cometary debris is of interest. The recent IUE observations by the U. of Maryland group, led by A'Hearn revealing dimer sulfur (S_2) emissions between

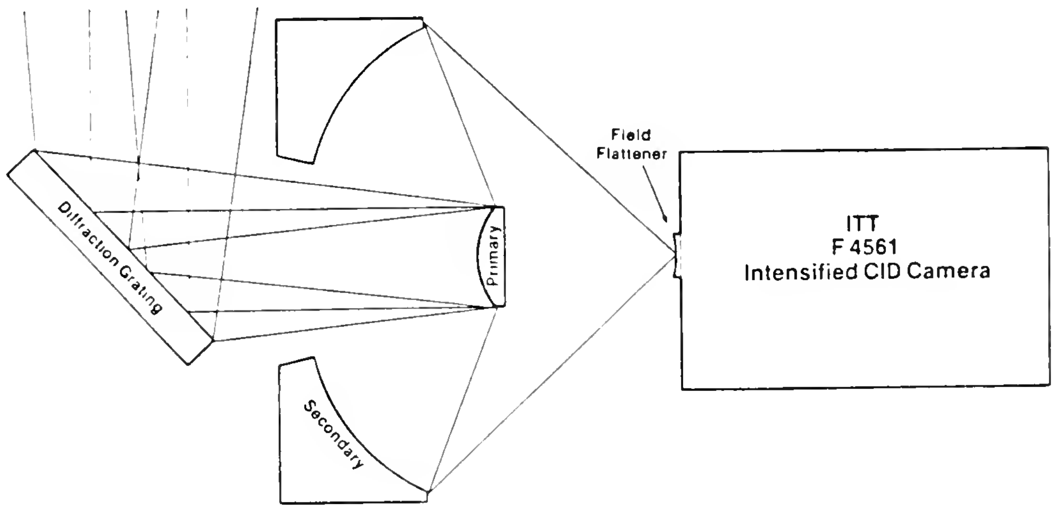
2820A and 3090A of comet IRAS-Araki-Alcock, makes the search for meteor sulfur all the more interesting.

5. SiO at 1310A.

Instrumentation. The experiment makes use of high speed (f ratio of 0.75) reflecting optics viewing a 12° by 12° field with an objective grating. The imaging detector is an intensified solid-state array having the following characteristics:

1100-3200A	6 ma/watt sens. (1500A)
UV intensified CID	20 ma/watt sens. (2500A)
244 x 388 pixels	$CsTe/MgF_2$ p.c./wind.
8.7 x 11.4 mm	ex. ITT F.4561

The dispersing element would be a 300 l/mm grating blazed for first order with a 250 A MgF_2 protective coating. Fig. 1 displays the proposed optical configuration.



In the GAS configuration, video data will be stored in a stack of up to four compact video cassette recorders. Depending upon recording speed, a total record duration for the four-stack would be eight to twenty-four hours. Because data is recorded for approximately twenty minutes per orbit, data would be gathered over twenty-four to seventy-two orbits. Control would be by microprocessor and total power required would be less than 1.2 KWH from a battery pack of less than 1 ft^3 and 100 lb.

A HITCHHIKER configuration would allow greater volume by utilizing shuttle power and additional GAS type containers for data storage. The optics/detector could then be gimbeled to allow pointing capability.

Comet Associated Meteor Showers (Cook 1973).

Shower & Comet	Dates	Peak Date
η Aquarids, Orionids, and P/Comet Halley[A,B]	Apr. 21-May 12 Oct. 02-Nov.07	May 03
Perseids and Comet 1862 III Swift-Tuttle[C]	July 23-Aug 23	Aug 12
τ Herculids and Comet 1930 VI Schwassmann-Wachmann 3	May 19-June 14	June 03
o Draconids and Comet 1919 V Metcalf	July 07-24	July 16
Annual Andromedids and the predicted orbit of P/Comet Biela for 1972	Sept. 25-Nov.12	Oct. 03
October Draconids and P/Comet Giacobini-Zinner 1946 V	Oct. 09	Oct. 09
Leo Minorids and Comet 1739 Zanotti	Oct. 22-24	Oct. 24
Pegasids, December Phoenicids, and Comet 1819 IV Blanplain	Oct. 29-Nov. 12	Nov. 12
Leonids and P/Comet Tempel-Tuttle 1965 IV	Nov. 14-20	Nov. 17
Monocerotids and Comet 1917 I Mellish	Nov. 27-Dec. 17	Dec. 10
Ursids and P/Comet Tuttle	Dec. 17-24	Dec. 22

A,B - Principle targets
C - Principle back up target

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THE ELECTROSTATICS OF A DUSTY PLASMA. E. C. Whipple and D. A. Mendis, University of California, San Diego, T. G. Northrop, Goddard Space Flight Center. We have derived the potential distribution in a plasma containing dust grains where the Debye length can be larger or smaller than the average intergrain spacing. We treat three models for the grain-plasma system, with the assumption that the system of dust and plasma is charge-neutral: a permeable grain model, an impermeable grain model, and a capacitor model that does not require the nearest neighbor approximation of the other two models. We use a gauge-invariant form of Poisson's equation which is linearized about the average potential in the system. The charging currents to a grain are functions of the difference between the grain potential and this average potential. We obtain expressions for the equilibrium potential of the grain and for the gauge-invariant capacitance between the grain and the plasma. The charge on a grain is determined by the product of this capacitance and the grain-plasma potential difference.

The three models give similar but not identical results. The results depend primarily on the parameter $Z = 4\pi\lambda^2 NC$, where λ is the Debye length, N is the grain concentration, and C is the grain to plasma capacitance. When $Z \gg 1$, the number of charges on a grain that is only charged by plasma currents is given by $(-Q/e) \cong [(\mu-1)/(\mu+1)][(\bar{n}_i+\bar{n}_e)/N]$ where μ is the square-root of the ion to electron mass ratio, and $\bar{n}_i$ and $\bar{n}_e$ are the average ion and electron densities. The charge on a grain in such regions is severely decreased from its free space value. The charge reduction occurs because the plasma electrons are depleted so that the grain does not need to be as negatively charged to equalize the ion and electron fluxes to its surface, despite the increased grain to plasma capacitance.

Workshop on the Interrelationships Among Circumstellar,
Interstellar, and Interplanetary Grains
February 27, 1985 - March 1, 1985: Aspen Institute, Wye, Maryland

WORKSHOP ISSUES

I. Circumstellar (C-rich; O-rich; H-poor/C-rich; novae; supernovae)

a. What relative contribution does each make to the ISM?
b. What is the chemical and isotopic composition of the outflow?
c. What is the crystal structure and morphology of the grains produced in the outflow?
d. To what extent will these grains trap volatiles?
e. What is the T,P profile of these shells as a function of R?
f. Are newly condensed grains processed in the CS environment?
g. What constraints do a-f place on IS and/or IP grains?

II. Interstellar (intercloud; diffuse, molecular, and dark clouds)

a. What is the size distribution and composition of grains?
b. How do the observed elemental depletions constrain models?
c. What grain processing occurs in the ISM?
d. How much time does an average grain spend in a particular environment?
e. Is any isotopic information available for IS grains?
f. What constraints do a-e place on CS and/or IP grains?

III. Interplanetary (stratospheric aerosols, relict meteoritic)

a. What is known about pre-solar matter in meteorites?
b. What is the morphology and crystal structure of primitive grains?
c. What is the chemical and isotopic composition of primitive materials?
d. What criteria can be used to distinguish primitive materials?
e. How does processing in the proto-solar environment and in the modern solar system affect the observed properties of IP materials?
f. What constraints do a-e place on CS and/or IS particles?

IV. Experimental Studies

a. What experiments have been done to study grain properties and processes?
b. How relevant are these experiments to astronomical problems?
c. What laboratory data, which is relevant to grain research but which has been obtained for other reasons, already exists?
d. What is the feasibility of experiments needed to obtain the data necessary to model relevant astrophysical processes?
e. What are the astrophysical implications of experimental simulations of cosmic phenomena?

ISSUES RESPONSE FORM

Name: Louis J. Allamandola

Date: February 25, 1985

Issue Number:
I. a, b, c, f, g.
II. a, c, d, e, f.
III. a, b, c, d, e, f.
IV. a, b, c, d, e.

Issue Restated:

Polycyclic Aromatic Hydrocarbons (PAHs) may be relevant to all three areas of circumstellar, interstellar and interplanetary particles, yet their properties under celestial conditions are virtually unknown.

Comments and Questions Regarding this Issue:

The recent suggestion of PAH-like species as carriers of the "Unidentified" IR (UIR) emission bands, the IR cirrus discovered by IRAS, the Visible Diffuse Interstellar bands (DIBs) and, by implication, other phenomena as well, raises many questions. The "match" between the IR absorption spectra of neutral PAHs with the UIR bands is very suggestive that PAH-like species are a ubiquitous component of circumstellar and interstellar dust. Under interstellar conditions PAHs should be ionized, and the observation of only one IR emission band at 11.3 microns implies that they are partially hydrogenated. Thus a study of the photochemistry, photophysics and spectroscopy of ionized, partially hydrogenated PAHs is imperative to test the hypothesis.

Experiments to be performed extend beyond the measurement of absorption spectra, and include transfer studies between the doublet and quartet states of ionized PAHs as well as fluorescence versus phosphorescence efficiency determination (i.e. - internal conversion - intersystem crossing branching ratios between excited electronic states as has long been done on the neutral species).

The thermodynamics of their formation in stellar atmospheres is extremely important. Most of our knowledge of thermodynamic stability comes from flame chemistry studies. There is a big difference between the normal terrestrial oxidizing flames and the highly reducing conditions in carbon star atmospheres. How stable are they really? How long can they survive in the diffuse interstellar medium and in H-II regions? Are what we believe to be PAHs primordial or recent? Do the PAHs and other carbonaceous material found in meteorites and solar system particles originate in circumstellar shells?

How big are they? Are we looking at species containing 20, 40, 60, 100, or even more carbon atoms? At what upper limit in size (carbon number) is it appropriate to treat PAHs as molecules? When is a bulk treatment appropriate? Does the 2-dimensional nature of PAHs preclude a bulk treatment?

ISSUES RESPONSE FORM

Name: Lou Allamandola **Issue Number:** II. a, b(?), c, d, e, f

Date: February 25, 1985

Issue Restated:

What are the interrelationships between interstellar dust in both dense and diffuse clouds and the connection with comets?

Comment:

A three pronged attack combining observations, experiments and theory is needed to address this extremely complex issue. Such an approach is required since the more fundamental questions to be asked are multidisciplinary in nature and the big picture will become clearer only once several of these have been addressed. Some (not all) of these questions follow.

1) What is the precise composition of interstellar grain mantles? Moderate resolution, good signal to noise spectra from 2 to about 14 microns can provide much of this information. To date, such observations, coupled with laboratory experiments and theory indicate that mantles in molecular clouds are made up largely, but not exclusively of simple molecules such as CO, H_2O, NH_3 and aliphatic hydrocarbons. Recent data in the 5-8 micron region indicates that more complex molecules such as aldehydes, esters, ketones and alcohols are also present. More data, both observational and experimental is needed to interpret these results and extract, more fully, the information that is in the observational data. For example, towards the protostar W33A, about 30% of the C and O are bound up in the mantle in the form of aliphatic ($-CH_2-$,$-CH_3$) groups and H_2O. About an additional 2-4% is in frozen CO. Very significant differences are seen towards other protostars. The differences provide a powerful diagnostic of conditions within each cloud as well as indicate the extent of chemical evolution which has occurred.

2) What is the connection between grain mantles in molecular clouds with the organic material apparently present in the diffuse medium? The presence of more complex molecules in grain mantles in molecular clouds provides strong evidence of energetic processing within the mantle itself in the dense cloud phase since the molecules cannot be produced in sufficient abundance by simple gas phase or grain surface reactions. Processing by ultraviolet photolysis or cosmic ray bombardment may be responsible. The significance of each process as well as their relative importance is controversial. Yet there is evidence that such processing takes place. It would be very useful to determine the maximum amount of energy deposited by the lower energy cosmic rays. A simple calculation indicates that this is not sufficient to account for the observations. As the volatiles evaporate, the mantle composition becomes dominated by the larger molecules. Is this the precursor of the organic material producing the 3.4 micron band in the diffuse medium? More observations of diffuse cloud material in the 3.4 micron region, though difficult, are needed in addition to further laboratory studies of these non-volatile residues.

3) What are the spectroscopic properties of polycyclic aromatic hydrocarbons (PAHs) suspended in ices? In addition to laboratory studies of ices containing simple molecules, PAHs should also be studied. Their spectroscopic properties in solids will be different from their properties in the gas. In molecular clouds, they should have accreted on grains. This may be one of the reasons why the absorption counterpart of the unidentified IR emission bands have not yet been detected. Of course, in addition to the spectroscopic properties of PAHs, the spectroscopic properties of the organic residue remaining after ices have been photolyzed should also be measured.

ISSUES RESPONSE FORM

Name: W. W. Duley **Issue Number:** II

Date: May 6, 1985

Issue Restated:

"Circumstellar grain formation" by Draine

Comment: "Carbon-Rich Outflows"

Recent laboratory work by Duley (Ap. J. 287, 694, 1984) shows that the carbon solid that forms via condensation of gaseous C, C_2 and C_3 contains a mix of trigonal (aromatic) and tetrahedral (diamond) bonding. Such amorphous material has no 220 nm resonance but absorbs strongly for wavelengths <160 nm. In partially hydrogenated form absorption features are seen at 3.3 and 3.4 microns that are quite similar to those observed in interstellar absorption.

Issue Restated:

"Observations and Theories of Interstellar Dust" by Mathis

Comment: "Theories of Grains"

A 220 nm absorption band is seen in Mg - silicate as well as in MgO. New lab data suggests that surface OH^- ions may be responsible. (Duley and Steel, unpublished work). The photo-excitation technique is a standard method for measuring weak absorption in gases and solids and is not controversial. However, for the record, an absorption band due to O^{2-} in MgO has been measured using conventional techniques (cf. Chen et al. Phil. Mag. 32, 99, 1975 fig. 1) and lies at 217.5 nm.

Issue Restated:

"Shock Processing of Interstellar Grains" by Seab and Shull

Comment:

It should be remembered that shocks need not lead to the immediate atomization of dust. Carbon dust, in particular, has been seen to dissociate into molecular fragments as well as atoms in lab experiments. Shocks can liberate large carbon molecules from dust in diffuse clouds; molecules that may be observable in absorption (cf. Duley and Williams. Mon. Not. Royal Astr. Soc. 211, 97, 1984).

ISSUES RESPONSE FORM

Name: Alain Leger **Issue Number:** II. a

Date:

Issue Restated:

Interstellar grains - Diffuse Bands

Comment:

It is proposed that the Polycyclic Aromatic Hydrocarbon molecules whose presence is inferred from IR emission of IS dust are good candidates for the carrier of the Diffuse Interstellar Bands (DIBs) in the visible.

The suggestion is based on the points:

- the ions of such molecules are expected to have transitions in the visible with appropriate widths.
- they can survive the UV photons present in the Diffuse IS medium where the DIBs are observed.
- they fulfill the criterion of abundance that one gets considering the intensity of the observed bands. This criterion is not fulfilled by many other suspected species.

Different implications of this suggestion should be checked in the future such as the absence of such bands in C poor regions.

A laboratory search for spectroscopic identification has been undertaken.

ISSUES RESPONSE FORM

Name: Alain Léger **Issue Number:** II. a

Date:

Issue Restated:

Polycyclic Aromatic Hydrocarbon component of Interstellar Medium

Comment:

The grain size distribution should be extended down to a limit which is fixed by a physical process like sublimation. For carbon particles in the Diffuse Interstellar Radiation Field, it is a radius of approximately 4 A. In fact, such carbon clusters in the presence of hydrogen are planar pre-graphitic molecules (or Polycyclic Aromatic Hydrocarbons = PAHs).

Such big molecules can accout for otherwise very difficult to explain observed phenomena: IR emission features at 3.3 - 6.2 - 7.7 - 8.6 - 11.3 microns, mid IR extended emission far from heating sources as extensively observed by IRAS.

Those pre-graphitic molecules are thought to be a major component of the IS medium. Their proportion to bigger grains seems to fluctuate from place to place. A typical value for Diffuse IS Clouds (Cirrus) is 10% of the dust mass and 5 times the surface area of bigger grains.

Issue Restated:

Grain size distribution in dark clouds

Comment:

There are several indications that grains are significantly bigger in dark clouds.

- The wavelength at which polarization is maximum in objects like BN is approximately 1.5 microns instead of 0.5 microns in the Diffuse Medium.

- From polarization measurements in the KL nebula it is clear that many IR sources are reflection nebula (IRC3, IRC4, ...). To have significant albedo at 3.4 microns you need grain size >0.5 microns.

This points to an increase in radius by a factor 3 to 5 which seems to imply coalescence of grains.

ISSUES RESPONSE FORM

Name: Joseph A. Nuth **Issue Number:** II. a, III. f

Date: December 16, 1984

Issue Restated:

Graphitic Carbon is Not a Major Component of the Interstellar Dust

Comment:

Previous dogma held that all pre-existing materials were vaporized during the initial collapse of the solar nebula; however, recent evidence suggests that many interstellar grains still survive in the solar system today. The isotopic compositions of many individual meteoritic separates and IDP's (Interplanetary Dust Particles) display signatures which suggest distinct astrophysical sites as the birthplace of particular grains. Carbonaceous components have been found which carry "Xenon HL" (thought to have formed via the r and p processes in the expanding shell around a supernova) and which also carry a relatively pure 14-Nitrogen signature. Similarly, s process xenon has been found associated with pure a 13-Carbon signature in a carbonaceous component of chondritic meteorites. This component likely formed in the shell of a carbon rich red giant. Virtually all of the carbon found in meteorites and IDP's can be characterized as "kerogen-like", a term used to describe all of the intermediate stages in the formation of coal - from peat to anthracite. Graphite is extremely rare in meteoritic material. Since we know that many carbonaceous grains survived the collapse of the solar nebula, that graphite is thermodynamically more stable than kerogen, and that graphite is very rare in most meteorites and IDP's, we have only two possible scenarios to explain our data. First, we can assume that some unknown process in the protosolar nebula selectively destroys graphite without also destroying kerogen and does so with a sufficiently high efficiency to drastically alter the interstellar graphite/kerogen ratio. Alternatively, we can assume that there was little, if any, graphite in the interstellar grain population of the Giant Molecular Cloud which subsequently collapsed to form the solar system. I prefer the latter explanation.

ISSUES RESPONSE FORM

Name: Joseph A. Nuth **Issue Number:** II. e, III. f

Date: December 16, 1984

Issue Restated:

A Constraint on Grain Destruction in the ISM from Meteorites

Comment:

A variety of isotopic anomolies have been discovered in carbonaceous chondrites and IDP's (Interplanetary Dust Particles) which suggest that many meteoritic grains formed in distinct astrophysical environments. Such materials not only survived the collapse of the protosolar nebula but also had previously survived passage through the ISM. These grains formed in novae, supernovae, carbon rich red giants, etc. The components which are known to be isotopically anomolous range in volatility from 26-Magnesium (previously 26-Aluminum) to noble gases like neon and xenon. Whereas refractory materials require the complete destruction of the grain to eliminate the signature, only relatively mild heating (875K-1375K) is needed to release trapped "Xenon HL" or "Neon E". If meteoriticists can reliably determine the relative abundances of such anomolous materials in present day chondrites and then extrapolate to determine the relative abundances of these grain components prior to the collapse of the solar nebula, astrophysicists could combine these estimates with theoretical mass loss rates and number densities of the appropriate stellar sources to independently calculate grain survival rates. Present day models of grain destruction predict grain lifetimes a factor of ten shorter than typical mixing times in the ISM; if this were true then all isotopic signatures would have been destroyed well before the individual grains were incorporated into the protosolar nebula and would not be observed in the meteoritic record.

ISSUES RESPONSE FORM

Name: Richard Puetter **Issue Number:** II. a

Date: February 28, 1985

Issue Restated:

Presence of polycyclic hydrocarbons in ISM

Comment:

The strength of polycyclic hydrocarbons is that they potentially explain the unidentified IR emission features and perhaps the IR cirrus seen by IRAS. Another possibility exists, however, i.e. excitation of common small abundant molecules by a typically sized interstellar grain which has acquired the expected electric charge ($r_g kT_e/e$ stat coulombs). Such a mechanism can rotationally pump molecules passing by charged grains. Coupling to vibrational modes then can excite rotation-vibration transitions. Stark-broadening of the rotation levels would remove the normal gas-phase rotational structure, and the strong rotational pumping would move the pure rotational emission from the far IR/radio to roughly 10 microns to explain the IRAS cirrus emission. Testing of this mechanism is hence critical since the operation of this mechanism would alleviate the need for the more "exotic" small polycyclic hydrocarbons. We are currently beginning a laboratory experiment to test this mechanism.

ISSUES RESPONSE FORM

Name: E. Whipple **Issue Number:** II. c

Date: February 28, 1985

Issue Restated:

Is the destruction of grains by interstellar shocks as large as is currently thought? Can current observations of interplanetary shocks shed light on the details of this process?

Comment:

The rate of destruction of grains by IS shocks is an order of magnitude larger than estimated rates of formation. IP and IS shocks are similar in some respects (densities, velocities) and different in other respects (e.g. magnetic fields). The details of IP shocks are well-observed and analyzed and can probably be extrapolated to IS shocks to obtain profiles of magnetic and electric fields through shocks. For example, there is an electrostatic potential drop across shocks which could affect the grain motion. Grains probably gyrate across the shock many times.

It would be useful to use a kinetic theory description of an IS shock (rather than a MHD description) and to follow a grain trajectory numerically with time-dependent charging of the grain to get a better estimate of destruction rates by sputtering and grain/grain collisions.

ISSUES RESPONSE FORM

Name: A. N. Witt **Issue Number:** II. a

Date: February 27, 1985

Issue Restated:

What is the size distribution of interstellar grains?

Comment:

Information regarding the typical size and the size distribution of interstellar grains can be derived from the following types of observations:

1. Wavelength dependence of interstellar extinction at wavelengths $\geq$912A.
2. Wavelength dependence of interstellar polarization.
3. Wavelength dependence of the phase function asymmetry of interstellar scattering.
4. X-ray scattering by interstellar dust.

Observationally, only item 1 has received extensive coverage so far. Unfortunately, the models devised to explain existing observations of interstellar extinction are far from unique.

Interstellar linear and circular polarization have only been fully explored for wavelengths $\geq$3000 A and they appear to provide information on a component of the interstellar grain spectrum which is dielectric in nature with a typical size 0.2 microns in radius. Observations in the UV are most desirable but could be inconclusive, if smaller interstellar grains are either spherical, optically isotopic or unalignable under interstellar conditions.

Item 3, interstellar scattering, promises to be a rich source of information on the size distribution of grains because the phase function asymmetry governing the redistribution of scattered light is strongly size dependent. So far, results are limited because of the difficulty of obtaining good observational data, especially in the UV, and because of remaining ambiguities concerning applicable scattering geometries.

Indications from the studies of the reflection nebulae NGC 7023, NGC 1999, NGC 1435, NGC 1432 and 17 Tau are: (1) the dust albedo in the UV is high (0.5 to 0.6 at 1500 A; (2) the phase function asymmetry undergoes a significant systematic change with wavelength in the region <4000 A towards a less forward-directed phase function at UV wavelengths. These results are in conflict with some currently widely accepted dust models, and, if correct, would indicate a much greater role for grains in the 10^{-6} to 10^{-7} cm size domain.

X-ray scattering by interstellar dust is most strongly influenced by the largest grains in the interstellar dust distribution. Information, even with future X-ray telescopes, will always be quite limited regarding the small-size end of the distribution.

ISSUES RESPONSE FORM

Name: A. N. Witt **Issue Number:** II. a

Date: February 28, 1985

Issue Restated:

Dust Scattering Properties in the UV

Comment:

The subject of dust scattering properties in the 1000 A to 3000 A wavelength region remains controversial. The MRN Model and Greenberg's model make very different predictions with regard to albedo and phase function asymmetry in this region, and I maintain that both are in conflict with observation. Reflection nebulae continue to show a decline in albedo from 0.6 to 0.4 from 3000 A to 2200 A, followed by a rise to 0.6 at 1500 A. Shortward of 1400 A the albedo appears to drop slightly. More in conflict are the results on the phase function: We find that the phase function changes throughout the UV from a strongly forward-directed form (g of approximately 0.6 to 0.7) at 3000 A to a more nearly isotropic (but still forward directed) form (g of 0.25 $\pm$ .10) at 1400 A. By contrast, Greenberg demands g>0.8 for the entire UV, while MRN expects approximately constant 0.5 to 0.6, with a rise to g>0.6 at wavelengths <2000 A. The resolution of this problem will bear heavily on what type of particles cause the 2200 A band and the far-UV rise in extinction.

Issue Restated:

The Asymmetry of the Scattering Phase Function

Comment:

The observation of surface-brightness profiles of high-galactic latitude globules (e.g. thumbprint nebula) provides the surest way to find the value of the phase function asymmetry of scattering by interstellar dust. (See Ap. J. 208, 709, 1976). One problem is that the dust in such clouds may be of larger size than in typical diffuse clouds. Great importance should be placed in obtaining UV photographs of such objects with the UIT in 1986.

ISSUES RESPONSE FORM

Name: A. N. Witt **Issue Number:** II. a

Date: February 28, 1985

Issue Restated:

Scattering Properties of Interstellar Dust Derived from Reflection Nebulae

Comment:

A frequently repeated argument is that the geometry of reflection nebulae is too uncertain to allow the reliable derivation of scattering properties from the observation of such objects.

1. There are approximately 250 cataloged reflection nebulae, yet virtually all work continues to be done with half-a-dozen objects. Why?: These are the objects of highest surface brightness. I contend these cannot be objects of arbitrary geometry but rather must be objects of near optimal geometry, and we know what these conditions must be.

2. Reflection nebulae are essential from the point of view of presenting a geometry which is independent of wavelength. This makes them ideal for studies of relative changes in optical properties of the scatterers.

Issue Restated:

Nature of Extended Red Emission in Reflection Nebulae

Comment:

Recent observations of reflection nebulae with B,V,R,I broad-band filters and CCD detectors have led to the discovery of extended red emission in the R and I bands. In the I band this excess emission is comparable in intensity to the dust-scattered light at I in the nebula, but it exhibits a spatial distribution much more strongly concentrated towards the illuminating star. The relative strength of the I excess reaches a maximum where the nebular color in the (B,V) range is bluest.

These observations can be interpreted in terms of a model which explains the extended red emission as a luminescence process excited by UV radiation from the illuminating star. The dependence of the red-emission intensity upon dust optical depth identifies the mid-UV region (1800 A to 2500 A) as the likely source of the exciting photons. Both the spatial distribution and the intensity of the extended emission in R and I suggest strongly that this emission is the short-wavelength tail of the near-IR extended emission discovered by Sellgren et al. in these same nebulae.

ISSUES RESPONSE FORM

Name: A. N. Witt **Issue Number:** II. a

Date: March 14, 1985

Issue Restated:

What constraints do X-ray haloes provide for the size distribution of interstellar grains?

Comment:

As discussed by Hayakawa (Progress of Theor. Phys. 43, 1224, 1970), the differential cross section of interstellar grains for scattering of X-rays varies as a^6, while the total cross section is proportional to a^4. Given that interstellar grains seem to follow a size distribution n(a) proportional to $a^{-3.5}$, one would conclude that both the shape of the X-ray halo as well as the amount of scattered X-rays for a given line of sight are essentially determined by the largest particles in the size distribution. Observations (e.g. Catura, Ap. J. **275**, 645, 1983) of X-ray haloes with the Einstein Observatory seem to place an upper limit of approximately 1 micron on the size of interstellar grains. In order to obtain constraints on the relative number of grains in the a $\leq$0.03 micron domain, observations of the faint outer parts of the scattering halo must be made with high accuracy, which is technically very difficult.

ISSUES RESPONSE FORM

Name: Mark Allen **Issue Number:** IV

Date: May 1, 1985

Issue Restated:

The need for laboratory studies of interstellar grain chemistry

Comment:

The development of models of the growth of interstellar grain mantles and of the impact of heterogeneous processes on the composition of the gas phase is hindered by the paucity of relevant laboratory data. The processes of adsorption/desorption, migration, and reaction of chemical species on astrophysically realistic surfaces under conditions similar to those of interstellar clouds need to be examined in detail, to do so may require the development of new experimental techniques. The following two examples illustrate how basic uncertainties in current astrophysical models require clarification by laboratory studies.

Interstellar grains residing in molecular clouds are thought to be coated with a mantle of volatile compounds that have condensed out at the low ambient temperatures. Observations of broad infrared absorption bands have been interpreted as indicating the presence in the grain mantles of H_2O [Whittet et al., <u>Nature</u>, **303**, 218 (1983)], NH_3 [Knacke et al., <u>Ap. J.</u>, 260, 141 (1982)], and CO and CN groups [Lacy et al., <u>Ap. J.</u>, **276**, 533 (1984)]. One point not easily derivable from the observations is the identity of the dominant component of the mantles. Laboratory experiments suggest that, at low temperatures characteristic of the molecular clouds, several monolayers of molecular hydrogen will accumulate on the surfaces of bare ice and silicate grains [Augason, <u>Ap. J.</u>, 162, 463 (1970); Lee, <u>Nature</u>, 237, 99 (1972)]. But the existence of large amounts of H_2 in the gas phase suggests that, whenever H_2 impinges on a grain, it desorbs quickly. Such a situation will result only if the mantles are predominantly composed of H_2 with the heavier molecules being embedded at low concentrations. This grain mantle composition would have properties significantly different from those of the more classical icy mantles.

Greenberg and Yencha [INTERSTELLAR DUST AND RELATED TOPICS, p. 369 (1973)] have proposed that simple molecules comprising grain mantles can be processed into more complex compounds if the mantles are exposed to ultraviolet radiation. In the laboratory simulations of the proposed phenomena [Hagen et al., Ap. Space Sci., 65, 215 (1979)], the integrated flux a grain would be exposed to as a consequence of its existing for millions of years in a weak, potentially highly attenuated, radiation field is reproduced by just scaling up the light intensity in the terrestrial apparatus. More complicated molecules indeed are synthesized in the laboratory experiments. The question is the validity of the radiation field scaling procedure. The timescale for producing a complex molecule from two simpler radicals is the timescale for the two radicals to find each other multiplied by an efficiency factor for producing the reactant radicals. This efficiency factor is the ratio of the timescale for photocleavage of the molecular bond to produce the radical, a function of the incident radiation field, to the timescale for reforming the bond from the two original product species. Thus when the radiation field is weak, the production of radical reactants is highly inefficient and the synthesis of more complex species is suppressed. On the other hand, in the laboratory experiment, the radiation field in unnaturally intense, allowing a critical concentration of radicals to be attained and subsequent complex molecule synthesis to be accelerated.

ISSUES RESPONSE FORM

Name: Gustaf Arrhenius **Issue Number:** IV. a, b, c, d

Date: February 26, 1985

Issue Restated:

What experiments have been done to study grain properties and processes?

Comment:

A fair number, but few of these (e.g. Meyer, 1971) attempt to realistically model the state of excitation of the medium, the electrodynamic properties of the grains and the pronounced thermodynamic disequilibrium between grains and the surrounding medium.

Issue Restated:

How relevant are these experiments to astronomical problems?

Comment:

Only to the extent that they attempt to realistically model the actual situation in space.

Issue Restated:

What laboratory data, which is relevant to grain research but which has been obtained for other reasons, already exists?

Comment:

Primarily extensive fundamental and applied data on growth of solids, including thin films from laboratory plasma and excited gas.

Issue Restated:

What is the feasibility of experiments needed to obtain the data necessary to model relevant astrophysical processes?

Comment:

Aside from necessary funding, the involvement of scientists whose first hand experience of the actual properties of the space medium derives from direct in situ measurements.

ISSUES RESPONSE FORM

Name: Gustaf Arrhenius **Issue Number:** IV. e

Date: February 26, 1985

Issue Restated:

What are the astrophysical implications of experimental simulations of cosmic phenomena?

Comment:

Because of the remoteness of objects studied by astrophysicists, it is not possible to resolve in sufficient detail the phenomena that control grain formation and related processes in other stellar systems. For this reason, most models used by astrophysicists are unrealistically homogeneous with regard to particles, fields and composition of the medium, and idealized physical and chemical behavior is frequently assumed. The somewhat increased resolution offered by satellite observatories to some extent improving the situation, but the necessary resolution to directly measure the crucial phenomena in remote stellar systems will probably never be achieved. Relevant observations that are now obtained with space probes within our solar system are, therefore, of utmost importance in guiding the reconstruction of past processes in our system and ongoing processes in other stellar systems. Comets provide useful probes of volatiles and grains introduced in the heliosphere (the sphere of action of the solar field, extending to the limits of the solar system). The magnetospheres of the planets provide other excellent conditions for studying particle-field interaction and defining the conditions on which dust processes (including grain formation, modification, and aggregation) appear to depend.

ISSUES RESPONSE FORM

Name: Bob Hazelton **Issue Number:** IV. d

Date: February 28, 1985

Issue Restated:

What is the feasibility of experiments to study grain processes?

Comment:

The study of grain-grain collision processes would be useful in determining the mechanisms of conglomeration of small particles or the fracturing or vaporization of larger particles in shock waves.

One method to study this is to produce variable velocity beams of grains which can then be collided at controlled relative velocities. By varying the charge state of low velocity particles, the effect of electrostatics on collision cross sections and sticking coefficients could be determined.

By accelerating the low energy particles via mass selective accelerators, high energy collisions could be produced in which the relative proportion of fragmentation or vaporization could be determined. Such a study would support theoretical work in the shock processing of dust grains.

ISSUES RESPONSE FORM

Name: W. Krätschmer **Issue Number:** IV. a, b

Date: January 31, 1985

Issue Restated:

Infrared small particle extinction of silicates of astrophysical importance.

Comment:

We studied the effects of structural disorder on the IR spectra of Mg-rich olivines. Significant changes occur in the small particle extinction if one moves from the crystalline to the amorphous state. Only the disordered silicate exhibits extinction maxima at 10 and 17 microns wavelength, i.e. at those wavelength positions at which the interstellar grains show extinction peaks as well.

The layer-type silicates abundant in C1 and C2 carbonaceous chondrites exhibit, in addition to the absorptions at about 10 and 20 microns characteristic features at and beyond 2.7 microns. These bands originate from OH groups and inter-layer water molecules. For structural reasons, OH groups have to exist within the silicate lattice of layer silicates, even if these silicates are completely water-free (e.g. in talc). The infrared OH-bands correlated in strength with the 10 (and 20) micron absorptions thus indicate the presence of dust consisting of layer silicates. This opens the possibility to distinguish observationally between layer- and other types of silicate dust in interplanetary and interstellar environments.

ISSUES RESPONSE FORM

Name: John S. Mathis **Issue Number:** IV. b, d

Date: February 11, 1985

Issue Restated:

How much yellow stuff is produced inside molecular clouds?

Comment:

As far as I know, "yellow stuff" is produced only under certain conditions. Mixtures of CO, H_2O, NH_3, etc. are deposited simultaneously onto cold surfaces in the laboratory, and the resulting ice layer is processed by UV photons or energetic protons. When the processed icy mixture of free radicals is warmed, gas is evolved and "yellow stuff" remains behind as a rather refractory residue.

In actual clouds, it is possible that water, etc., are frozen out much more sequentially; H_2O and NH_3 first, and then CO. Lacy et al. (Ap. J., **276**, 533, 1984) show spectra of sources deep within molecular clouds. All show the 3.07 micron "ice" band. Some show a band of solid CO; another a line of gaseous CO. Thus, "ice" and CO surely freeze out at different times.

My question is whether or not "yellow stuff" will be produced if water and ammonia are deposited first on a cold surface, and then CO. The lack of physical proximity between the two substances, except at the surface in between the layers, might make a large difference in the yield of the refractory residue. This question can be answered by existing equipment. Maybe it already his been.

Issue Restated:

What are the indices of refraction of "yellow stuff" in the visual?

Comment:

Linear and circular polarization combine to show that the grains which provide the visual polarization are very good dielectrics. If the visual extinction is provided by mantles of silicates coated with "yellow stuff" (the refractory residue which remains after icy mantles of free radicals are warmed), then the mantle must be a dielectric. It would be very interesting to determine the optical constants of the "yellow stuff" produced in the laboratory. In fact, all one really needs to do is to see if it is a dielectric. The fact that it looks yellow in the visual makes me suspect that it must absorb some colors better than other ones, or that it can't have zero absorption at all visual wavelengths.

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16. Abstract

Proceedings of a workshop held at the Aspen Institute's Wye Plantation Conference Center in Wye, Maryland, from February 27 to March 1, 1985. The workshop was attended by 50 astronomers, astrophysicists, planetary scientists and meteoriticists; and emphasized the interdisciplinary nature of studies of cosmic dust.

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